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**NAVAL
POSTGRADUATE
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MONTEREY, CALIFORNIA

THESIS

**ANALYSIS OF INTERACTIONS OF LOGISTICS ELEMENTS
OF K-1 TRACKED VEHICLES IN THE REPUBLIC OF
KOREA ARMY BY USING SIMULATION MODEL**

by

Si-Won Park

June 2007

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TRACKED VEHICLES IN THE REPUBLIC OF KOREA ARMY BY USING
SIMULATION MODEL**

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MASTER OF SCIENCE IN OPERATIONS RESEARCH

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ABSTRACT

The K-1 Tracked Vehicle (K-1 TV) has been the main battle tank of the Republic of Korea Army (ROKA) for the last twenty years. Maintaining the highest level of combat readiness of the K-1 TV is one of the most critical missions for ROKA logisticians. This research focuses on the improvement of the depot level maintenance (DLM) since it has considerable influence over the combat readiness of the K-1 TV.

A simulation model of the DLM process has been built. Four major logistics elements are the input parameters: component failure rate, repair rate, inventory service level, and logistics delays. The model with these logistics elements is simulated for the acquirement of data and the results provide guidance about the interactions of logistics elements.

The analysis of the results shows the effective procedures and the significant elements during DLM of the K-1 TV. In conclusion, the procedures of the analysis give valuable insights related to the methodologies of analysis of the logistics elements and facilitate logisticians to conduct the efficient logistics support.

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EXECUTIVE SUMMARY

The K-1 Tracked Vehicle (K-1 TV) has been the main battle tank of the Republic of Korea Army (ROKA) for the last twenty years. Maintaining the highest level of combat readiness of the K-1 TV is one of the most critical missions for ROKA logisticians. This research focuses on the improvement of the depot level maintenance (DLM) since it has considerable influence over the combat readiness of the K-1 TV.

This thesis explores the DLM of the K-1 TV process and focuses on four major logistics elements as the input parameters: component failure rate, repair rate, inventory service level, and logistics delays. The specific research questions concerning these logistics elements are described below:

1. What logistics elements can affect the total maintenance cycle time of the depot for the K-1 TV?
2. Are there any significant interactions among logistics elements?
3. How should one measure significant interactions of logistics elements and how should one analyze the relationship between logistics elements and total maintenance cycle time of the depot?
4. What are appropriate Design of Experiment (DOE) methodologies for the analysis of logistics element interactions from the simulation model?

The simulation model with these logistics elements employs dynamic, discrete, and stochastic events based on the scenarios for the DLM process of the K-1 TV of ROKA. The model obtains the total cycle time of DLM for the analysis and provides guidance on the interactions of logistics elements.

The purpose of the thesis is to assess how changes of input parameters related to the logistics elements affect the results, combat readiness and readiness risk. Sixty-seven factors are selected as logistics elements for the analysis of the DLM of the K-1 TV, and the settings of these factors range from 10% below to 10% above the base scenario values. The research uses space-filling Nearly Orthogonal Latin Hypercubes (NOLH) experimental designs and a robust design approach, to allow the exploration of a large number of input parameters in an efficient number of runs and to evaluate whether the model results are relatively insensitive to uncontrollable sources of variation present in the system's environment.

The data analysis of the outputs from NOLH and robust design use regression tree and multiple regression analysis to accomplish the following tasks:

- Identify factors and interactions that have significant impact on the results;
- Estimate the average cycle time of DLM for the K-1 TV
- Compare the influence on the MOEs between using the simple moving average method and the weighted moving method for forecasting within the DLM process; and

- Analyzing the robustness of the results to the decision factors' settings.

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I. INTRODUCTION

A. BACKGROUND

The Korean Peninsula is located in the center of the northeast Asia, and has served as a bridge between powers on the continent of Asia and powers of the Pacific. This fact of geographic location has always been the most significant effect to Korean history. Because of its strategic location, Korea has experienced many wars against other countries. Normally the counter-part countries were the most powerful countries at that time, without Korea's intention on fighting wars. In recent times, Korea suffered from the invasion of Japan and experienced the Korean War approximately 60 years ago. Korea became a divided country, and subsequently the arms race between North and South Korea began. At first, North Korea overwhelmed South Korea with not only its military power, but also its economic size. But South Korea's economic development was much more rapid than North Korea's and South Korea kept increasing its defense ability. Today, South Korea overwhelms North Korea economically, and is capable of defending itself against the threat of North Korea's military power (see Table 1).

	Gross Domestic Product (2005)	National Defense Expenditures (2005)
Republic of Korea	\$7,879 billion	\$210 billion
North Korea	Below \$250 billion	\$18 billion

Table 1. GDP and NDE Comparisons between ROK and NK

For the last two decades, the Republic of Korea Army (ROKA) has made remarkable improvement in the quality of weapon systems. ROKA succeeded in improving military power not only by purchasing high-tech weapon systems, but also by starting localization of weapon systems. Since the late 1970's, ROKA has tried to localize weapon systems in many fields and has achieved the successful localization of several weapon systems. This means that ROK has the capability to defend the Korean Peninsula against North Korea and any other potential enemies.

From the basic weapon systems like ammunitions and small arms for infantry soldiers to the high-technology weapon systems like the main-battle tanks and the self-propelled artilleries, ROKA has completed localization.

As the weapon systems of ROKA have become diversified and complicated, ROKA should focus on the logistics systems to keep the high readiness of weapon systems. Even if a weapon system has better military strength than any other system, its performance can be wretched unless a logistics system can support it. Inefficient logistics support also brings vast maintenance costs.

ROKA has already introduced and applied the concept of Integrated Logistics Support (ILS) to deal with these problems. ILS is the activity that manages the whole logistics support, from the acquisition of a weapon system to its eventual discard, in order to keep up the strength of weapon systems and the efficiency of logistics support. Ideally, ILS can provide logistics support at the right time at the right place at the right cost, and minimize the life cycle cost of weapon systems. ILS needs appropriate Logistics Support Analysis (LSA) to perform such

activities. This thesis starts from this background. Since it is difficult to systematic collect and analyze real-world data, ILS cannot currently be performed very well. This thesis deals with how to develop the logistics system by analyzing the logistics elements, and gives a methodology and insights about how to make efficient and effective logistics support.

ROKA has faced the significant challenge of keeping the strength of weapon systems high while staying within a limited budget. Since the weapon systems are developed and evolved very dynamically, the traditional ways of performing the maintenance of new weapon systems can easily cause more problems than before in many fields. As previously mentioned, the analysis of a logistics system is essential to achieve the successful ILS.

B. BENEFIT OF THE STUDY

This thesis is based on the premise that the systematic analysis of logistics supports is needed as the weapon systems become more sophisticated. A simple problem, if uncorrected, can cause significant damage as the system grows bigger and more complicated. For example, an error that occurred at the planning stage might cause big problems at the last step. In other words, a small change at the last step could have big ramifications, such as high costs or low readiness.

The solution is quite obvious. Everything would be fine if ROKA could increase the budget of the maintenance process of each weapon system and should improve the efficiency of each logistics systems. But the problem is that it is impossible to increase the budget without any reasonable data. The important thing is how we could

estimate the proper budget to keep the constant maintenance process without diminishing combat readiness. So, the only way to solve this problem is that logisticians should be more professional and well-educated in developing their ability to understand more sophisticated logistics systems and to adjust the dynamic changes of logistics. This thesis will study and analyze a logistics system of one specific weapon system, the K-1 series tracked vehicle, which was invented and localized by ROKA. Since the K-1 series tracked vehicle accounts for a majority of the entire fleet of tracked vehicles of ROKA, it is very important to keep the highest combat readiness of K-1 series tracked vehicles by using the most efficient logistics system. But it does not matter which weapon system is selected since this thesis focuses on how to analyze logistics systems, not considering just one specific case of a single weapon system. If logisticians know the underlying concepts and the methods for analyzing the K-1 series logistics system, they can adapt and apply it to the other logistics systems without significant efforts. In other words, this approach can help logisticians gain intuition and a better understanding of a specialized logistics systems.

Even if a weapon has the highest-tech system, it becomes useless and gives a painful headache to ROKA if a logistics system cannot provide adequate support. These kinds of weapons tend to easily break down if not maintained correctly, and costs lots of money to maintain. Logisticians should be more specialized and more professional in dealing with these weapon systems. That is the fastest and easiest way to save money and time, decrease the cost of maintenance, and increase the combat

readiness of weapon systems. The purpose of this thesis is to determine how to analyze the logistics system to improve the efficiency of logistics support for keeping the highest combat readiness with the fixed maintenance budget. It can help logisticians to understand and to analyze the logistics system.

C. RESEARCH SCOPE

This research will focus on the maintenance process of the K-1 TV based on logistics systems of ROKA. There are several levels of the maintenance for the K-1 series tracked vehicles: unit level of maintenance, intermediate level of maintenance, and depot level of maintenance. Since it is restricted to get the data of the whole levels of maintenance, it needs to be more simplified and to make the scope made narrower. This research considers only the depot level of maintenance since it has the most substantial effect on the combat readiness and the cost of the whole maintenance levels as a whole.

D. THESIS ORGANIZATION

Chapter II introduces the integrated logistics system (ILS) of ROKA. It provides an overview of the K-1 series tracked vehicle (K-1 TV), which is the main battle tank of ROKA and is a high-technology weapons system. It explains the background of the logistics system that supports the K-1 TV by separating several logistics elements. Chapter III discusses how to model the logistics systems and explains how to approach the solution. It describes the selection of factors included in the model. Chapter IV provides an analysis of the model output data and shows an example of several methodologies that can be used to address the output data for the solution. Chapter V provides conclusions and recommendations for follow-up research.

E. RESEARCH QUESTIONS

This study considers logistics elements of depot level maintenance of the K-1 TV. The main purpose shows how to analyze these elements by using a simulation tool. The more detailed questions to answer in order to make sure the main goal is met are as follows:

1. What logistics elements can affect the total maintenance cycle time of the depot for the K-1 TV?
2. Are there any significant interactions between logistics elements?
3. How should one measure significant interactions of logistics elements and how should one analyze the relationship between logistics elements and total maintenance cycle time of the depot?
4. What are appropriate Design of Experiment (DOE) methodologies for the analysis of logistics element interactions from the simulation model?

II. MODEL DEVELOPMENT

A. OVERVIEW

This chapter provides the reader with the information and the approach used to build the model. It provides the background of the K-1 series tracked vehicle and introduces the logistics concepts to support the maximization of the operational availability of the K-1 TV. It also shows the scenario that which explains the procedure of depot level maintenance of the K-1 TV in ROKA.

B. K-1 SERIES TRACKED VEHICLES

In the 1970's, Republic Of Korea Army (ROKA) faced extreme shortages in fighting power of Main Battle Tanks (MBT) against North Korea Army's MBT. Even though ROKA had retired M-4A3E, which was a relic of WWII, the number of MBT was half the amount of North Korea's, and the capability of MBT was also significantly poorer than North Korea's. At that time, MBT of ROKA was made up of the M-48 Tank which was armed with a 90mm smoothbore gun. It was evaluated as the tank of the transition period from WWII at that time. M-48 was not the tank with modern technology. The 90mm smoothbore gun developed from the M-190mm anti-aircraft gun in WWII was aimed to encounter Tiger Heavy series tanks of Germany. In contrast to the MBT of ROKA, North Korea's MBT was the T-62 series, which was in the second generation MBT. The M-48 had several shortages in comparison with the T-62 series. The 90mm smoothbore gun of the M-48 could not penetrate the front armour of the T-62. The M-48 did not have any kind of night-vision equipment and used a gasoline engine.

As a countermeasure, ROKA tried to import an M-60A1, but it was canceled because of financial problems and political conflicts with the US and ROK. Even if it executed successively, it was impossible to change the whole fleet of MBTs from M-48 to a new series of tank, such as the M-60 series; and there was also a 'plan-B' which was the schedule to upgrade to M-48A3 or to M-48A5. The important thing was that it had been more than ten years since the M-60A1 had developed at that time. Because of that, ROKA considered that the M-60 series was not the newest technological tank. Other countries, such as the United States and Germany, had already been developing the next generation tank series enhanced by the newest technology.¹

In the late 70's, the latest technologies used in the development of new MBT were already completed to apply to the old version of MBTs. These conditions gave ROKA no choice but to import the next generation of tanks. So, they decided to create the next generation MBT for themselves. Since ROKA did not have any experience and technology to develop MBT, it looked like an impossible mission. Because of that reason, ROKA chose an international vender. It was processed in a unique way. The main idea of this tender was that the international incorporation created MBT in other places or other countries, and then the production of MBT would be conducted in Korea. Chrysler defense Inco was selected among several international incorporations in 1981. But Chrysler defense Inco was disposed to General Dynamics since Chrysler was in financial crisis at that time. The whole process of developing MBT for ROKA was

¹ Yun Hyung Jin, A proud main battle tank of ROK Army, K-1 & K-1A1, <http://www.defence.co.kr/>.

conducted by General Dynamics Land System (GDLS). Since GDLS had developed M-1 Abrams series vehicles simultaneously, many parts of the basic components of MBT of ROKA were shared with M-1 Abrams MBT, and the shape of MBT also looked similar to that of M-1 Abrams. The development of ROKA's next generation MBT was completed in 1988, and the prototype was delivered to ROKA in the same year. The mass - production of the new MBT had begun in 1990, and Hyundai was selected to conduct this process. The first opening to the public of the next generation MBT was held in 1987, and was named 88 Tank by the President of the Republic of Korea since the 1988 Olympics were held in Korea. But the formal name was ROKIT (ROK Indigenous Tank). It was the origin of the K-1 series tracked vehicles. After that time, K-1 series tracked vehicles have been the main part of military tracked vehicles (MTV) in ROKA.

Hyundai has developed the K-1 series of tracked vehicles: K-1A1 120mm MBT, K-1 105mm MBT, K-1 Armored recovery vehicle (ARV), and K-1 Armored Vehicle Launch Bridge (AVLB). K-1 series vehicles are built at the Hyundai Precision and Industry Company Ltd (HDPIC) automated production facility at ChangWon.²

K-1A1 is an upgraded version of the K-1 MBT. The main difference is that it is enhanced by a 120mm M256 smoothbore gun, which is also installed on the US M1-A1/2 MBT. Samsung Electronics, now Samsung Thales, are providing the fire control system including the Korean Commander's Panoramic Sight (KCPS) which includes a thermal imager with 288 x 4 focal plane array, KGPS gunner's sight with thermal

² Hyung Jin, A proud main battle tank of ROK Army, K-1 & K-1A1, Retrieved April, 2007, from <http://www.defence.co.kr/>

imager, eye safe laser rangefinder and dual field of view day TV camera and KBCS ballistic fire control computer.³

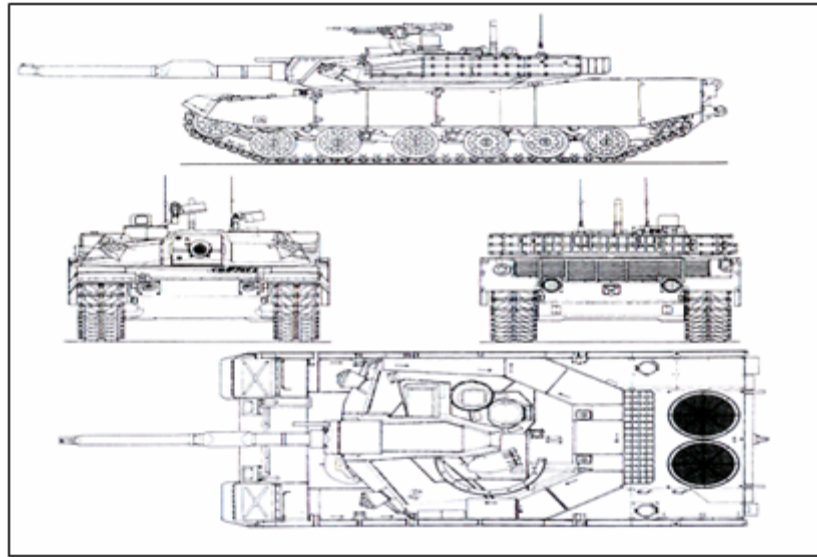


Figure 1. K - 1 Main Battle Tank

C. INTEGRATED LOGISTICS SUPPORT

1. Overview

As previously mentioned in the background section, ROKA carries out Integrated Logistics Support (ILS) to hold up weapon systems economically and efficiently. The goal of this thesis is also to provide the ways and the intuition to logisticians to perform successful ILS. Since ILS is also applied to K-1 series tracked vehicles, it needs to go into further detail to understand the concept of logistics support.

ILS is the activity of management of the whole logistics elements from the requirement of the weapon system to the plan, development, acquisition, and discard of weapon system for efficient and economic logistics support.

³ Army-Technology, K-1/A1 Main Battle Tank, South Korea, Retrieved April, 2007, from <http://www.army-technology.com/projects/k-1/>.

In summary, ILS activities:

- Keep the strength of weapons systems and the connection between weapons systems and logistics support.
- Incorporate organized logistics elements.
- Perform the acquisition of logistics elements and the deployment of it simultaneously.
- Maintain the acquisition of logistics elements and the application of it.

ILS should be developed together with the development of a weapons system, and should consider not only typical elements but also incorporate elements like plans, analysis, and estimations.

2. Function of Integrated Logistics Support

The purpose of ILS (Integrated Logistics Support) is to acquire the right logistics elements and to provide the weapons system at the right time, at the right place, and at the right cost. ILS is always needed during the whole life cycle of a weapons system. Figure 2 shows an ILS application.

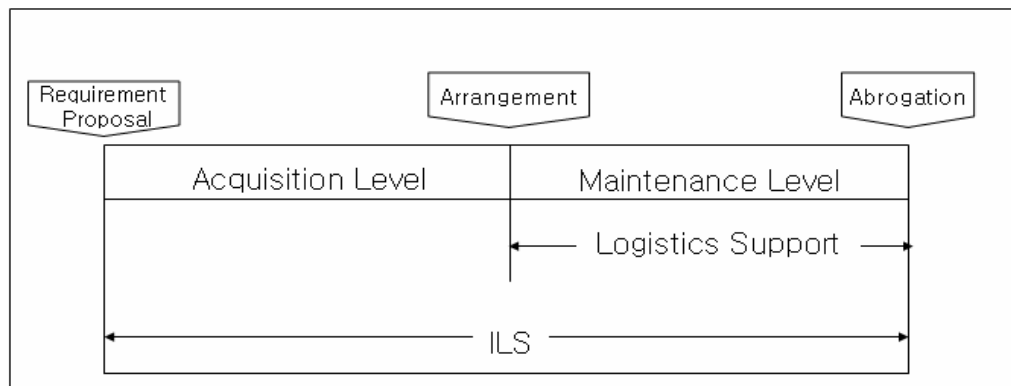


Figure 2. ILS Application

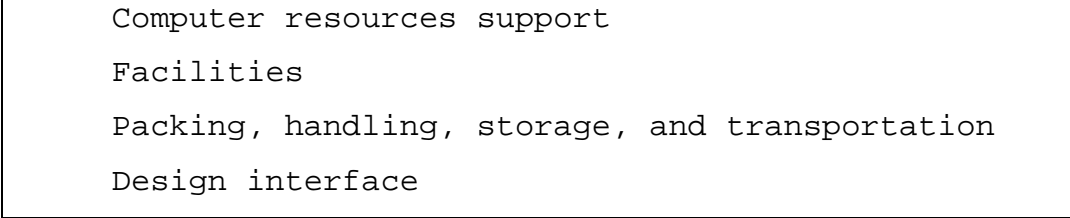
Specially, ILS is significantly needed at the acquisition level of a weapons system, like the development of the concept of a weapon system, and the plan of acquisition. Since the utmost part of the Life Cycle Cost (LCC) is usually decided at the early stage of acquisition of a weapons system, the weapons system without the consideration of Operations and Maintenance (O&M) cost has not only the vast O&M cost but also the limitation of modification of the design process or the manufacturing process if they need to be modified when some problems are occurred. That is to say, it is very difficult to modify the design of the process if ILS does not work at the early step of acquisition.

The most important condition for successful ILS is at the facility of logistics support. ROKA should keep up the effort to develop the systemic collection of O&M data of similar weapons systems, as well as the scientific analysis and evaluation. The final purpose of this thesis also helps to build the appropriate criterion.

3. ILS Elements of the Republic of Korea Army

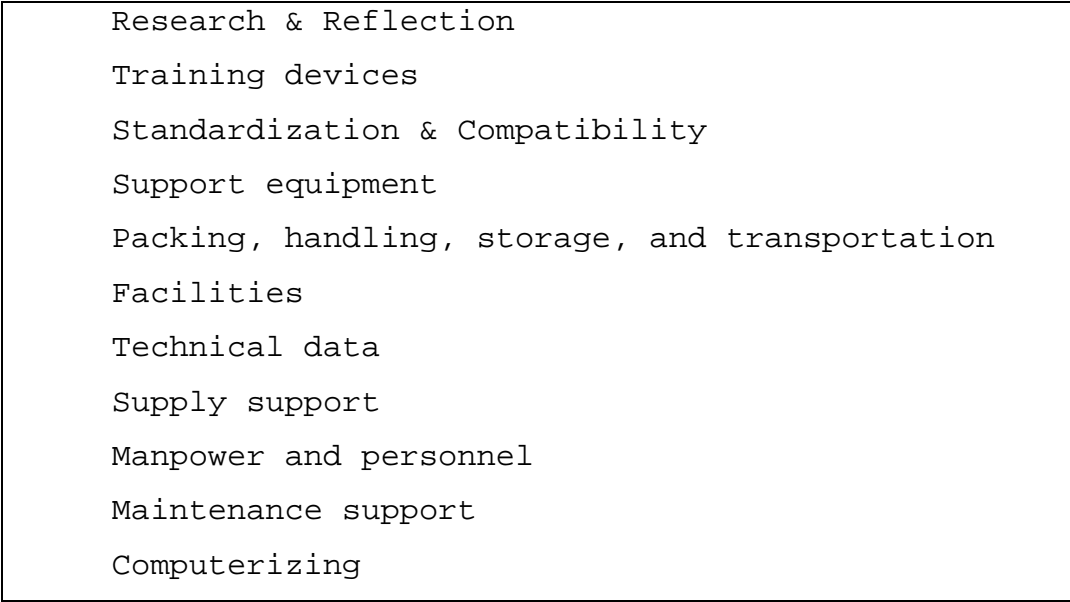
ROKA modeled on ILS elements of the United States Army for the first time in 1983. It started with the 9 elements of the US Army (Figure 3), and went through the several modifications to finally confirm 11 elements for ROKA (Figure 4).

Maintenance planning
Manpower and personnel
Supply equipment
Technical data
Training and training support



Computer resources support
Facilities
Packing, handling, storage, and transportation
Design interface

Figure 3. US Army ILS elements (2005)



Research & Reflection
Training devices
Standardization & Compatibility
Support equipment
Packing, handling, storage, and transportation
Facilities
Technical data
Supply support
Manpower and personnel
Maintenance support
Computerizing

Figure 4. ROKA ILS elements (2006)

Since this thesis concentrates on the logistics support of K-1 series tracked vehicles, especially the depot level maintenance (DLM), it only describes specific ILS elements instead of describing the entirety of elements.

a. Support Equipment

Support equipment is a very important part of sub equipment to put in practice or to sustain a weapons system. The emphasis of this element is to assess the quality of sub equipment, like a list of items or a distinctive quality, and to estimate the required quantity of sub equipments needed for the complete acquisition. Support equipment is able to affect the amount of maintenance affairs, and not only dominates the reliability and the effect of a weapons system, but also occupies the majority

part of the entire cost of the ILS process. Examples of detailed support equipment are listed below.

- Test estimation and inspection equipment.
- Measurement equipment and rectification equipment.
- Commodity manipulation equipment: forklift, tow car, and crane.
- Assistance equipment: generator, cooler & heater.
- Proximity maintenance support equipments.

In DLM for K-1 series tracked vehicles, support equipment comes under the repair part. The repair part also significantly affects to the total time of maintenance. This conception is very important and is able to affect to the total time of maintenance.

b. Supply Support

Supply support entails the entire executions of the assessment of the requirement, the acquisition of support commodity, and the support of human resources. The important part of supply support is the Early Level of Preparation (ELP) for logistics supports. This means that the process includes the estimation of the required sorts of support items, the approximate quantities of support items, and the execution of acquisition during the first several years, normally three years, of deployment of a new weapon system. Since ELP considerably affects the operational capability of a weapons system, it needs the precise execution related with this element.

DLM always calls for the supply support to maintain K-1 Tracked Vehicles (K-1 TV). If there is not enough supply support at the depot, the total time of maintenance and the cost of maintenance are supposed to

increase substantially. Since the prediction of the proper amount of supply support is very important, this thesis takes into account the concept of this element.

c. Maintenance Support

This element is directly related to the DLM of the K-1 TV. It shows how DLM works in ILS as one element of ILS. During the life cycle of a K-1 series tracked vehicle, maintenance support is necessary for the management of the entire maintenance process with ease by the analysis of elements based on the maintenance procedures and the establishment of the maintenance plan. The concept of maintenance is based on the concept of operational capability of weapon system and is supposed to be set up before the design of a weapons system. The maintenance concept includes a sub-process of maintenance, a principle and a responsibility of each sub-process, an available maintenance time, and a condition of maintenance support. This element is supposed to provide the foundation for the assessment of capability of logistics support and to provide the ability to estimate the amount of logistics support required and the establishment of a maintenance plan.

D. LOGISTICS ELEMENTS OF DEPOT LEVEL MAINTENANCE

This thesis is concerned with four logistics elements during DLM based on ILS element concepts, support equipment, supply support, and maintenance support. Each element is systemically connected to each other and articulates the action of itself in the depot level of maintenance. Four logistics elements are as follows:

- Component Failure Rate.
- Component Repair Rate.

- Inventory System Level.
- Logistics Delay.

The complete process of DLM for the K-1 TV is composed of these logistics elements. The analysis of these elements for the efficient management of DLM as a logistics support for the K-1 TV is the object of this thesis.

A simulation model is constructed to represent the condition of DLM, and these four elements are considered as input data of the simulation model. An output is monitored by changing these input data to analyze the effect of the input data. These logistics elements will be explained more and apply to the condition of DLM.

1. Component Failure Rate

Component Failure Rate (CFR) determines how often a K-1 TV goes to the depot because of failures. To understand CFR, we need to consider the level of maintenance first.

There is a maintenance policy of the K-1 TV in the logistics system of ROKA. This system breaks maintenance levels into three components: unit level of maintenance, intermediate level of maintenance, and depot level of maintenance.

For example, unit level of maintenance includes simple repairs or replacements, and intermediate level involves more difficult repairs or replacements than the unit level of maintenance. Depot level is the ending level among levels of maintenance and can deal with major overhauls.

There are two cases that lead to the depot for an overhaul. The first case is the K-1 TV reaches a certain age which ILS set at the acquisition level. The second case is the K-1 TV breaks down and is only able to get the

repair service at the depot. The first case takes a regular period time and costs a fixed amount of the budget, but the second one has large variability of time and normally takes longer to complete DLM than the first one. The first case is called the mean interval of scheduled maintenance ($MTBM_s$), and the second case is called the mean interval of unscheduled maintenance ($MTBM_u$). The mean or average time between all depot level maintenance actions (corrective and preventive) is calculated by the summation of these two values.⁴

$$MTBM = \frac{1}{1/MTBM_u + 1/MTBM_s}$$

As previously mentioned, the regular age is decided before the maintenance of K-1 TV and is fixed value. The inter-failure time to go to the depot is a variable related to CFR. To define this variable, the concept of Mean Time Between Failures (MTBF) is generally used. MTBF is the average time between failures, or the reciprocal of the failure rate in the special case when failure rate is

⁴ Benjamin S. Blanchard, Logistics Engineering and Management, Prentice Hall Industrial and Systems Engineering: 5th ed, 1998.

constant. To get the exact value of MTBF is to use the historical data of the K-1 TV during the life cycle of the K-1 TV, where:

Once these are determined, we can analyze the effect of circumstances like operation missions, maneuver distance, the condition of terrain, and humidity on MTBF. Since it is restricted to make practical application of real data, it needs some stochastic assumptions to set MTBF. The number of failures to occur during the specific time is meant to be a stochastic process and follows a Poisson process such that the time between failures are independent and identically distributed exponential random variables having a mean of $\frac{1}{\lambda}$.

It is especially important to obtain the accurate CFR since the efficiency and the economy of DLM is greatly affected from CFR. So, it is decidedly one of the logistics elements of DLM of the K-1 TV.

2. Component Repair Rate

DLM of the K-1 TV ensures the continued integrity of operational capabilities of the K-1 TV and the preservation of disruption related with complicated systems throughout its service. This comprises carrying out maintenance beyond the capabilities of the lower levels, generally on equipment requiring major overhaul or the rebuilding of end items, subassemblies, and parts. ROKA operates one depot, called Consolidated Maintenance Depot (CMD), and there exists another depot which is maintained by Hyundai Rotem Corporation (HRC) as an outsource of ROKA.

The process of DLM starts when an unserviceable depot-level repairable vehicle is turned in to the unit level or

intermediate level maintenance, and it ends when the item is recorded on the inventory control point records as being ready for issue(RFI).⁵ The total time of DLM includes shipping and processing time, accumulation time, repair time, time awaiting parts, and delivery time. Unserviceable items may remain in storage for various reasons for extended periods of times.

DLM of the K-1 TV is categorized as scheduled and unscheduled as already described for CFR. If it is unscheduled maintenance, it costs extra money and affects the combat readiness of the K-1 TV. CMD has built up a standard process of maintenance of the whole weapons system. The process is further described below in Figure 5:

⁵ Keebom Kang, Susan M. Sanchez, and Kenneth Doerr, "A Design of Experiments Approach to Readiness Risk Analysis," *Proceedings of the 2006 Winter Simulation Conference*, L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nichol and R. Fujimoto, eds., pp. 1332-1339, Institute of Electrical and Electronic Engineers, Piscataway, NJ, 2006.

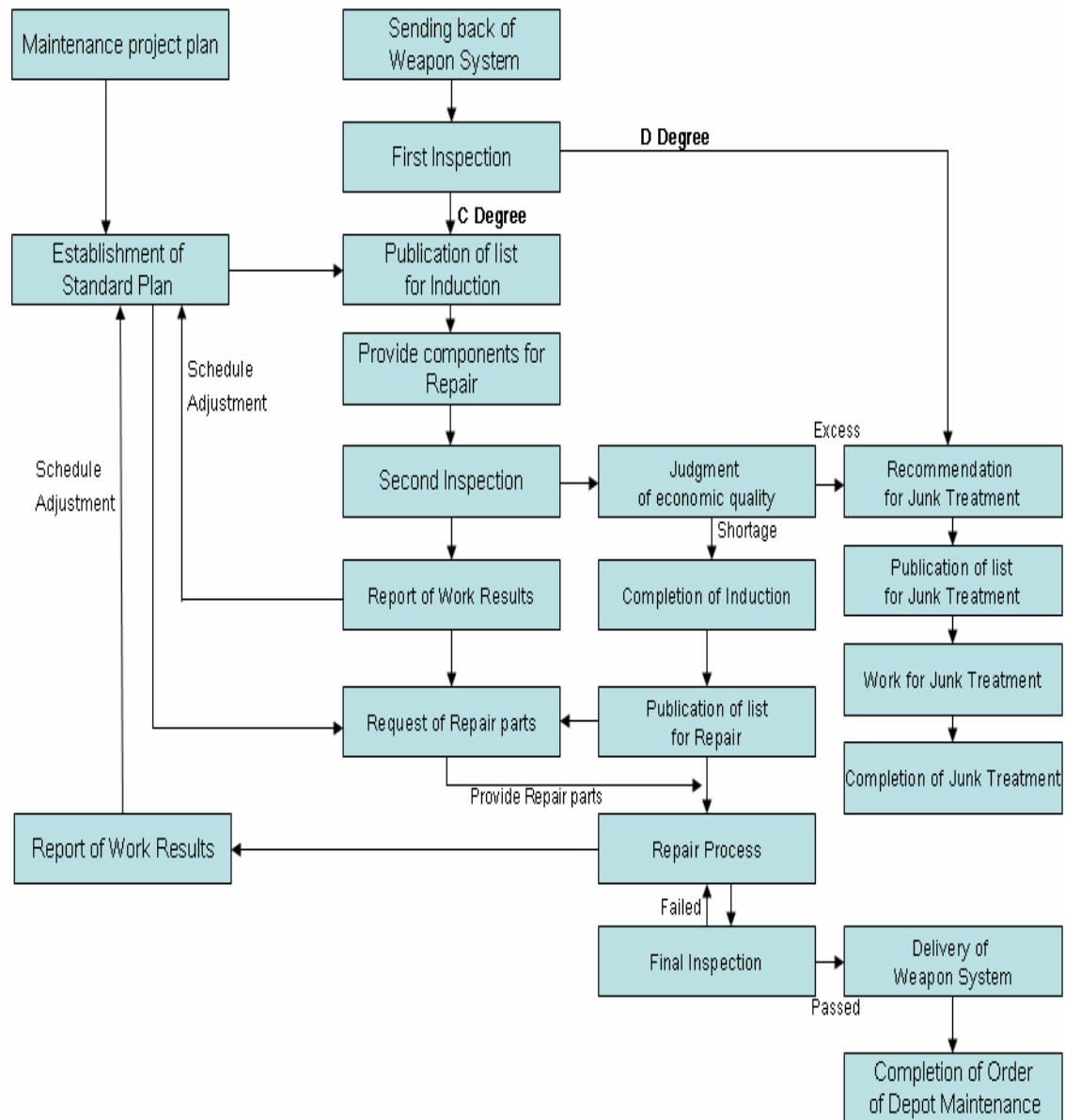


Figure 5. Flow of CMD Maintenance Process⁶

As you see the flow chart above Figure 5, the variability of each sub process can affect to the total time of DLM. If some processes take a long time during DLM, Component Repair Rate (CRR) has connected with the other logistics elements and is able to affect the combat

⁶ Republic of Korea Army Consolidated Maintenance Depot, Flow of CMD Maintenance Process, Retrieved April, 2007, from <http://www.tmd.mil.kr/portal>.

readiness of the K-1 TV or the life cycle cost of the K-1 TV. For example, if it fails the first inspection or the third inspection, the depot needs some repair parts or spare parts to fix the failed parts, and then it is connected to the inventory service level of depot, which will be explained later in this thesis. It also takes additional time to complete the whole repair cycle of the K-1 TV at the depot and causes a bad effect to combat readiness. If there exists no repair parts at the 'Request repair parts' process, it needs to reorder them from out-sources and costs a lot of money since it is always more expensive to reorder repair parts or spare parts. Because of that, it is meaningful to analyze the CRR process and its effect based on their variability and how their interactions work with each other. Consequently, CRR has a significant effect on not only the total time of DLM, but also on the total cost of the repair process of the K-1 TV.

3. Inventory Service Level

Since the K-1 TV is a high technology weapons system, it is vastly worthwhile to supply repair parts and spare parts at the right place, the right way, and at the right time. It is impossible not only to conduct the successful operation but also to get the economic maintenance of the K-1 TV without the precise prediction of demands and the adequate level of total stock of repair parts or spare parts. The precise forecast of demand of repair parts is always a big issue among logisticians, and ROKA gets into trouble when they minimize the supply postponement due to a lack of stocked items. Figure 6 depicts a maintenance system to estimate supplement demand.

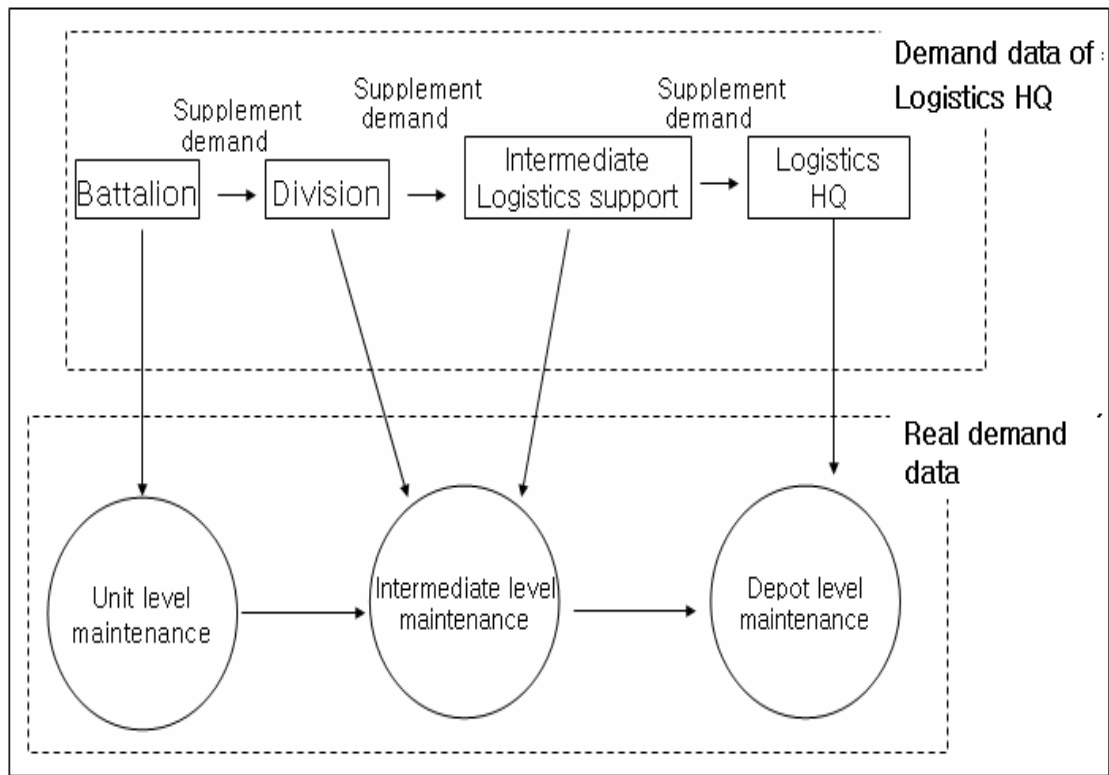


Figure 6. Maintenance systems to estimate supplement demand

It is very difficult to apply the appropriate methodology to predict the precise demand of each part given various conditions. ROKA already has applied some methodologies to get the precise forecasted demands to minimize the supply postponement. It will be a good experiment to analyze those methodologies applied to DLM of the K-1 TV.

Since this thesis is based on DLM only, it does not take into consideration ISL of the other level of maintenance and does not look into all the repair parts of the K-1 TV. The important thing is to understand the concept of ISL. Seeing as the goal of this thesis is to provide ideas to analyze the logistics elements for efficient logistics support, it does not matter whether the

completed real data is considered or not. Even if the model shows ISL of DLM only, it can be extended to the other level and detailed level of repair parts if we have an enough intuition based on ISL.

a. Characteristics of Repair Parts of the K-1 Tracked Vehicle

Repair parts are materials needed to repair a weapons system. The organization of repair parts is described below in Figure 7.

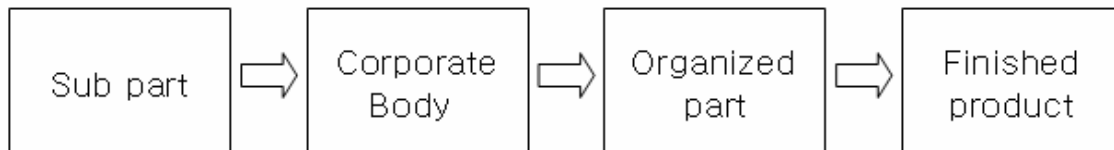


Figure 7. Organization of repair parts

Characteristic of repair parts based on the K-1 TV are as follows:

- Total number of repair parts is too numerous.
- Discernment of repair parts is too difficult.
- Prediction of demand of repair part is too difficult.
- Honest commodity should be supplied to the depot.
- Suitable time of supply is important.
- Stabilized and long term supply is limited.

Because of those characteristic, it is very difficult, and also important, to get the precise data for the forecast of demands. There have been several methodologies to get accurate prediction values, and ROKA

also has developed them for logistics support of the K-1 TV. Methodologies which ROKA frequently uses will be introduced next.

b. Methodologies for Forecasted Demands

Methodologies which ROKA uses are based on a 'time-series' model. They have analyzed patterns of demands during the past and applied them to predict of demands. The typical methodologies based on 'time-series' are the moving average method and least square method.

The moving average method calculates the average value based on time-series data over a period of time. The average value moves or changes as the aged data is removed and the new data is included by time-series arrangement. Even though the precision of prediction is lower than any other method, it is used broadly because of easy calculation. ROKA uses the simple moving average method and weighted moving method for forecasted demand⁷. The simple moving average method considers unsteady fluctuation only and removes it.

$$Y_t = \frac{\sum_{i=1}^n A_{t-i}}{n}$$

Y_t : Forecasted demands for next t^{th} time period

A_{t-i} : Actual demands of the $(t-i)^{th}$ time period

n : number of time period involved⁸

⁷ Republic of Korea Army Headquarter, Management of demands, Filed Manual, p.2~33.

⁸ Whee Sun Lee, Study of Forecasted Demands of Repair Parts K-1 Tracked Vehicles, M.S Thesis, AA 400030, National Defense University Republic of Korea, 2005.

The weighted moving method gives a weight to the recent data as it is close to the forecasted demands. Since the data close to the forecasted demands tends to have more of a relationship with forecasted demands, it is possible to get a more reliable prediction with weighted data.

$$Y_t = \frac{\sum_{i=1}^n W_{t-i} A_{t-i}}{n}$$

Y_t : Forecasted demands for next t^{th} time period

W_{t-i} : Weighted value of $(t-i)^{th}$ time period

A_{t-i} : Actual demands of the $(t-i)^{th}$ time period

n : number of time period involved⁹

c. Design of a Prediction Model of Repair Parts and Spare Parts

A prediction model of repair parts and spare parts can be designed by using prediction methodologies. At the first step, it needs to collect data. The data is then sorted by variables affect to the prediction, maneuver distance, time period, condition of terrain, atmospheric temperature, humidity, expertise of the driver, etc. At the second step, it applies several prediction methodologies to find the most proper method to get reliable forecasted demands. At the last step, we estimate errors between the prediction model and the real data by using simulation and analyze each of the prediction models. Prediction models of ISL can be qualitative variables of DLM. It is clear how

⁹ Whee Sun Lee, Study of Forecasted Demands of Repair Parts K-1 Tracked Vehicles, M.S Thesis, AA 400030, National Defense University Republic of Korea, 2005.

accurate the prediction model can affect to the combat readiness or repair cost of the K-1 TV.

4. Logistics Delay

When each K-1 TV goes to the depot for an overhaul, there are some transportation processes and administrative processes for DLM. Logistics Delay (LD) includes the whole delay time and additional cost from the post of the K-1 TV to the depot and from the depot to the post after maintenance. If there are some inefficient processes during LD, it does affect the total time of DLM of the K-1 TV and also gives an effect to combat readiness. It is very important to check inefficient LD processes and to analyze the interactions of them to maximize the efficiency of DLM.

In Korea, the transportation infrastructure consists of highways, railways, and waterways. Military transportation is usually concerned with highways and railways only. Especially, the case when the K-1 TV goes to the depot for an overhaul, which is made up of railways only since the K-1 TV can not go to the depot for itself. ROKA Logistics Support Command (ROKA LSC) manages several transportation groups which administer the entire military freight transportations. They check all the weapon systems of ROKA which need an overhaul at a depot level and plan the transport schedule for them within a budget. There are lots of weapon systems that need DLM in ROKA, and it makes LD tend to be more increased and to be the most time consuming process of any other logistics elements. ROKA LSC should arrange the order of priority based on the importance of the weapons system and set the order of priority based on the order of the K-1 TV failures that need DLM. If there is no system to control these

arrangements, it is obvious that LD should be increased and the combat readiness of the weapons system including the K-1 TV should be down even if the other logistics elements are perfectly organized for the logistics support of the weapons system. In other words, even if the K-1 TV approaches the age for an overhaul, it should wait at the post until the railway schedule for it becomes available. If the K-1 TV passes the age, it can not be operated as a military power since it is more likely break down and causes more expensive maintenance costs. If LD happens to be increased because of its inefficiency planning or executions, it has a significant effect on the combat readiness of the K-1 TV and takes a long time in the repair cycle of DLM. Thus, this thesis is concerned with LD as one of the logistics elements of DLM.

E. SCENARIO DESCRIPTION

This chapter describes a hypothetical scenario based on DLM of the K-1 TV. All of the data in this scenario have been assumed and approximated since some of the real data are classified and too hard to collect. Even if the scenario can not embody the exact same model of the real world, it is okay that the descriptions and the assumptions have reasonable data and values since the objective of the study in this thesis is not to embody the exact same model but to show the methodologies of analysis of interactions of logistics elements for the embodiment of DLM of the K-1 TV. This scenario explains the annual process of DLM of the K-1 TV.

1. Annual Program of Depot Level Maintenance of the K-1 Tracked Vehicle

DLM of the K-1 TV is performed by the Consolidated Maintenance Depot (CMD) of ROKA, and Hyundai Rotem

Corporation (HRC) is an outsource depot. Missions of CMD are to provide maintenance, and to produce parts and assemble parts into a complete package, to support logistics to the operating forces, and to manage DLM for maximization readiness and sustainability of weapon systems. CMD can handle between seventy and eighty K-1 TVs for maintenance per year, and HRC can handle approximately the same amount of K-1 TVs.

There are several types of K-1 TVs: K-1A1, K-1 ARV, and K-1 AVLB. When all types of these K-1 TVs go to the depot for overhauls, it is assumed that they receive the same service, which includes service time, workers for restoration of the K-1 TV, repair parts and spare parts, and transport means are the same in the model of this thesis.

It is assumed that ROKA operates 1500 K-1 TVs and has a policy to get DLM of the K-1 TV, called periodic examination, as shown below in Table 2.

Age	Maneuver distance
10 years	10,000 km

Table 2. Cycle of K-1 TV for an overhaul to depot

If the K-1 TV approaches one of these conditions, it is left out of the formation of an operating force and stays at the post until the transport schedule will be available for DLM. Approximately 10% of the whole fleet of K-1 TVs approaches this policy each year, and they ought to go to the depot.

The excepting to following this policy is the K-1 TV can go to the depot because of a break down which the other

levels of maintenance can not handle. The ratio of this case is between 10% and 15% of the average number of K-1 TVs which should go to the depot each year, and it is assumed that the K-1 TV in this case gets the same service as the K-1 TV of periodic examination. Actually, it is not true, but it is too restricted to describe all the different maintenance processes given various conditions. So, this thesis assumes they get the same service as each other, but if it is possible to collect the exact data of the depot, CMD or HRC, we can assume the maintenance process of each different case of a break down of a K-1 TV, and it will be a more reliable model and be able to give the detailed results of DLM.

2. Transportation Condition for an Overhaul of the K-1 Tracked Vehicle

ROKA LSC plans the transport schedule of all the military equipments within ROKA, including the K-1 TV for overhauls to the depot every year. During the last quarter of year, ROKA LSC brings together the information of periodic examination cases of all of the operating forces which operate K-1 TVs and completes the development of the transport schedule for the following year. If a break down of a K-1 TV occurs, the K-1 TV in this case is listed as the priority order of the next transport schedule and is able to use the next scheduled Military Freight Train (MFT).



Figure 8. Trailer for heavy weighted equipments

Since the K-1 TV can go to the depot by using railways only, ROKA LSC designates specific stations for MFT nearby each post to load the K-1 TV onto the MFT. The K-1 TV can move from the post to the station by using the specific trailer which is organized to higher level of units, such as divisions or corps. A trailer for heavy equipment is shown in Figure 8.

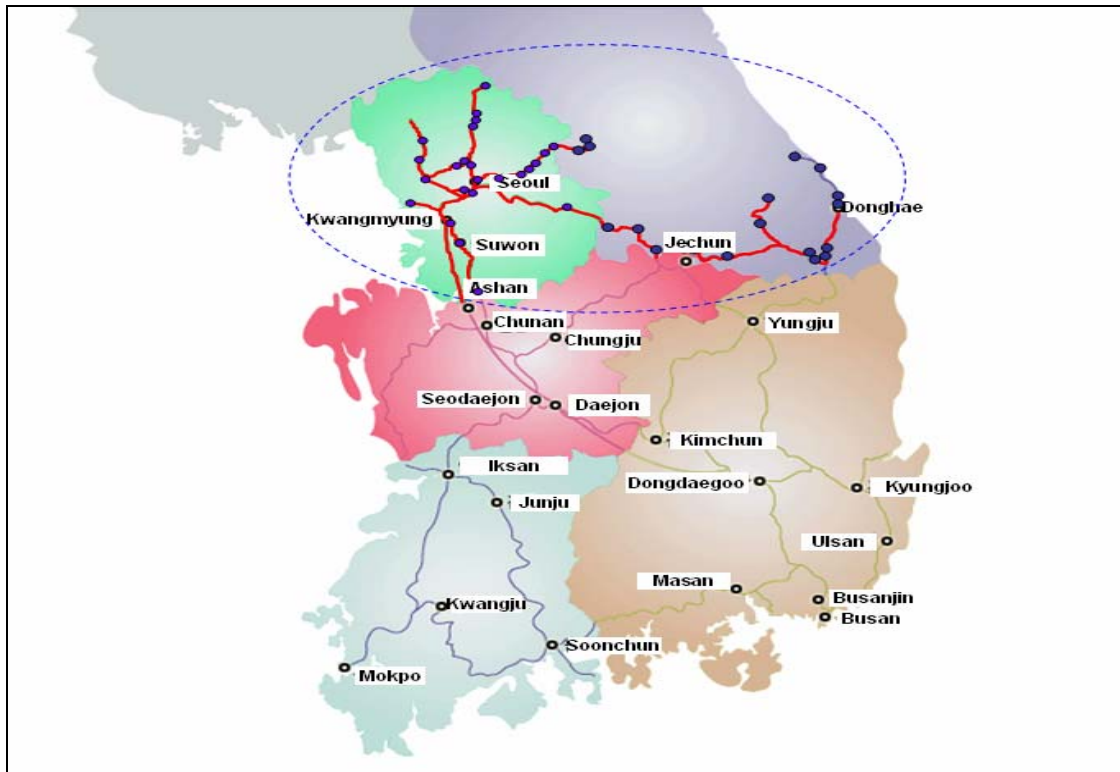


Figure 9. Railways of Korean Peninsular

The map in Figure 9 shows the railways of Republic of Korea (ROK). The region inside the blue oval is not only the center of the Korean Peninsular, but also borders against North Korea (NK). The green region, the northwestern part of ROK, is called Great Seoul Metropolitan Area and has 23 million people, and 47.1% of the county's population is centered at this region.¹⁰ It is noticeable that this region is strategically the most important place of ROK against NK. The blue region, the northeastern part of ROK, is also an important region since there are several roads which the mechanized forces of NK can use during wartime, and NK invaded ROK with these roads

¹⁰ Young-Sik Jeong, Optimal Military Transportation in a Korea Theater, M.S Thesis, Operation Research Department, Naval Postgraduate School, Monterey, CA, 2006.

during the Korean Civil War. The main power of ROKA is centered in these two regions, including mechanized forces with the K-1 TVs.

As you see in the railways of these two regions, there are several sub-railways and interactions of them. The stations which ROKA LSC designated nearby each post are on the sub-railways, which mean that there should be sub-trains that can move on sub-railways for loading military equipment (ME) including the K-1 TVs. These sub-trains that are loading ME should meet together at an intermediate station to make a combined completed MFT to go to the depot together. An intermediate station is shown in Figure 10.



Figure 10. An intermediate station

Since ME should be kept under watch of guards all the time, they can not stay for too long on the railways. When ROK LSC plans a railway schedule to transfer ME to the depot, ROK LSC sets the schedule of sub-trains and a large combined MFT to be performed at the same time. Normally, it does not take more than 24 hours from loading ME at

stations to making a large combined MFT at an intermediate station. Then the combined MFT goes to the depot directly.

During the peace time, the military transportation schedule (MTS) of ROK railway schedule is not the priority of the order, but the last order of ROK railway schedule. It makes constraints when ROK LSC plans MTS and causes Logistics Delays.

3. Repair Parts of K-1 Tracked Vehicles at the Depot

The number of repair parts of the K-1 TV is roughly 100,000. Since they are too large in number, this thesis focuses on 10 major repair parts that are considered the most important and frequently used during DLM, and they are simply labeled as A, B, C in the model because they are classified. ROK LSC plans the demand of repair parts of the following year and purchases forecasted repair parts during the last quarter of the current year.

When a K-1 TV goes to CMD or HRC, there are two inspection processes for the request of repair parts to repair a K-1 TV. It is decided what kind of repair parts are needed during these processes. The proportion of the repair parts needed for the repair process is depicted below in Figure 11.

Proportion of repair parts needed

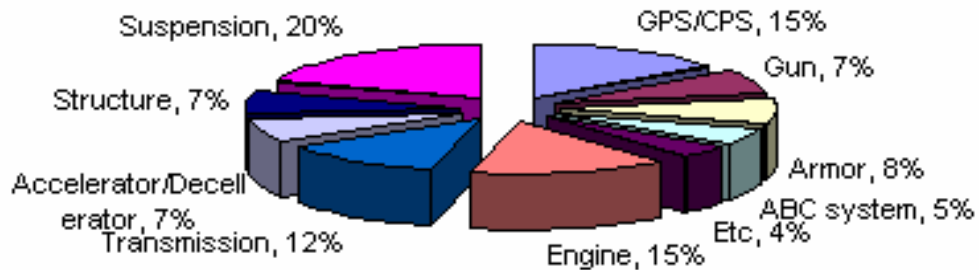


Figure 11. Proportion of repair parts needed

If the lack of repair parts is incurred before the end of year, the depot should reorder them to HRC, an outsourcing which has a capability to supply them. It normally takes more than one month and holds up the repair process until the repair parts become available. It is also true that the reorder process of each repair part has different arrival times and incurs additional reordering costs. However, they are assumed to be the same process in the model because it is limited to get real data. If logisticians who are in charge of planning the real processes based on DLM can understand the concept of this background, it is easy to extend the details close to the real situation, and therefore get more reliable results.

III. ANALYSIS METHODOLOGY

A. OVERVIEW

This chapter explains how to build the model, the variables based on the scenario, the measure of effectiveness, and the design of experiments. The objective of the analysis is to analyze interactions of four logistics elements and measure the effectiveness of DLM.

B. MODEL SELECTION

1. Simulation Model for Embodiment of Depot Level Maintenance of the K-1 Tracked Vehicle

This section briefly introduces a simulation model in general. Simulation model refers to a broad collection of methods and applications to mimic the behavior of real systems, usually on a computer with appropriate software.¹¹ As computers and software are better than ever, simulation is also more popular and powerful than ever. Among diverse kinds of simulation models, it needs to be classified to model DLM of the K-1 TV.

a. Characteristics of Simulation Models

There are three characteristics of simulation models for DLM of the K-1 TV. First, time does play a role in the model. Since each variable is changing based on time flow, the model needs to consider the concept of time, and this type of model is called a dynamic model.

Second, each state of the process or each variable changes only at separated points in time, such as the breakdown of a K-1 TV occurring at a specific time, and breaks taken by workers. This type of model is called a discrete (or discrete event) model.

¹¹ Kelton W.D., Sadowski R.P., and Sturrock, D.T., Simulation with Arena, McGraw-Hill Higher Education: Singapore, 3rd ed., 2003.

Last, there are some random inputs in the model. This means that the model operates with at least some inputs being random variables. For example, the breakdown of a K-1 TV occurs randomly. Since the uncertainty is usually present in the real DLM, the model should also involve random values. This is called a stochastic model.

Therefore, the simulation model for DLM of the K-1 is dynamic, discrete, and stochastic.

b. Pieces of Simulation Model

There are several pieces in the simulation model to represent DLM for the K-1 TV. The ones the model is chiefly concerned with are the following: entities, attributes, variables, and resources. With these pieces we can set the simulation model. Each of the listed pieces is defined below:

- o Entities: they are "players" of a simulation model. They move around, change status, affect and are affected by other entities and the state of the system, and affect the output performance measures. In the dynamic model, they are created, move around for a while, and then are disposed of as they leave. In this research, the K-1 TV and repair part are able to be independent entities as "players" of DLM.
- o Attributes: they are common characteristics of all entities, but with a specific value that can differ from one entity to another. The values of attributes are tied to specific entities. The same attribute generally has different values for different attributes. For example, each K-1 TV gets an Identification Number (ID) as an

attribute, but the ID number is different for each vehicle.

- o Variables: they are pieces of information that reflect some characteristic of the system. Variables are not tied to any specific entities, but rather affect the whole system in the model. They are also able to work as statistical accumulators. The logistics elements described in Chapter II can be variables of this simulation model.
- o Resources: they can represent a group of several things like workers, equipment used to repair a K-1 TV, or space to repair K-1 TVs in a depot area. Entities seize a resource when it is available and release it when it is finished.

2. Arena 10.0 for the Simulation Model

The simulation model of this thesis is embodied by using Arena version 10.0 (Kelton et al, 2007). Arena simulation software is a decision-making tool that analyzes a business, service, or nonmaterial-handling intensive production processes. It transforms a process flowchart into a simulation model to visualize a process with animation and to produce statistical outputs for analysis.¹² The developers of Arena give an application of Arena software as below:¹³

"Arena software enables you to bring the power of modeling and simulation to your business. It

¹² W. David Kelton, Randall P. Sadowski, and David T. Sturrock, *Simulation with Arena*, McGraw-Hill, Higher Education:Singapore, 3rd ed., 2003.

¹³ ROCKWELL SOFTWARE, *Arena User's Guide*, Publication ARENA-UM001B-EN-P - October 2005.

is designed for analyzing the impact of changes involving significant and complex redesigns associated with supply chain, manufacturing, processes, logistics, distribution and warehousing, and service systems. Arena software provides the maximum flexibility and breadth of application coverage to model any desired level of detail and complexity.

Typical scenarios include:

- Detailed analysis of any type of manufacturing system, including material-handling components.
- Analysis of complex customer service and customer management systems.
- Analysis of global supply chains that include warehousing, transportation, and logistics systems.
- Predicting system performance based on key metrics such as costs, throughput, cycle times, and utilizations.
- Identifying process bottlenecks such as queue build ups and over-utilization of resources.
- Planning staff, equipment, or material requirements."

Arena is also well-designed for use as an object-oriented design for entirely graphical model development and is able to set up a simulation model by having a user place graphical objects called modules on a layout in order

to define the model.¹⁴ Since it facilitates quick scenario setup and is well recognized with many built-in tutorial simulations, Arena was chosen to represent DLM of the K-1 TV.

C. VARIABLES OF INTERESTS

The next step is to identify input variables based on the background of logistics elements which were described in Chapter II.

1. Component Failure Rate

Component Failure Rate (CFR) is how often the failure of a K-1 TV goes up to go to the depot. Before setting the variables associated with CFR, the fixed assumptions related to CFR should be specified.

- Total number of K-1 TVs is 1,500.
- Time between failures follows an exponential distribution.

Since it is assumed that the average number of periodic cases per year is 10% of the total number of K-1 TVs, and the average number of failures per year is between 10% and 15% of periodic cases, the equations of CFR are as follows:

$$CFR = \frac{1}{E(\text{time between scheduled maintenance})} + \frac{1}{MTBF}$$

$$E(\text{time between scheduled maintenance}) = \frac{365 \text{ days}}{(Total \text{ number of } K-1TV) \times P_A}$$

$$MTBF = \frac{365 \text{ days}}{((Total \text{ number of } K-1 \text{ TV}) \times (1 - P_A) \times P_F) '}$$

where

¹⁴ David A. Takus, David M. Profzich, Arena Software Tutorial, Proceedings of the 1997 Winter Simulation Conference, Systems Modeling Corporation, Sewickley, Pennsylvania, 1997

P_A = Probability that a K-1 TV requires maintenance during a particular year,

MTBF: Mean Time Between Failures, and

P_F = Probability that a failure occurs requiring depot level maintenance for the K-1 TV during a particular year.

Table 3 outlines the variables chosen for the model. Each variable is varied over a range in order to evaluate the underlying effects on the output. Each variable type is described in detail below in the table.

Variable ID	Variable description	Min value	Max value
ProbAge	Probability to approach the age for an overhaul	0.09	0.11
ProbFailures	Probability of failures needs depot maintenance	0.1	0.15

Table 3. Variables of CFR

2. Component Repair Rate

The Component Repair Rate (CRR) is how often the depot can complete DLM of a K-1 TV during the specific time. The entire process of DLM is defined as events, resources, and variables in this model.

The events of DLM of a K-1 TV are:

- First inspection process,
- Induction process,
- Repair process,
- Final inspection process, and
- Junk treatment.

In order to conduct these events, the depot needs resources. Resources in this model are several types of workers, and are defined below:

- Repair workers (RW),
- Final inspection workers (FIW), and
- Junk treatment workers (JTW).

Repair workers are responsible for the first inspection process, induction process, and repair process. Final inspection workers conduct the final inspection process, and junk treatment workers perform the junk treatment process. A group of workers conducts the mission as a team, and a team is responsible for one K-1 TV until its task is completed. In other words, a team cannot conduct its mission with multiple K-1 TVs at the same time. After finishing its mission for one K-1 TV, they can move to the next vehicle. Table 4 shows more detailed assumptions of workers conditions for the model.

Workers' condition	Assumptions	
Working days	From Monday to Friday	
Working hours	8 hours, 0800~1200, 1300~1700	
Number of teams	RW	7
	FIW	5
	JTW	3

Table 4. Assumptions of workers as resources of model

The example of the actual model embodied by using Arena is depicted below in Figure 12 and shows how to set these assumptions in the model.

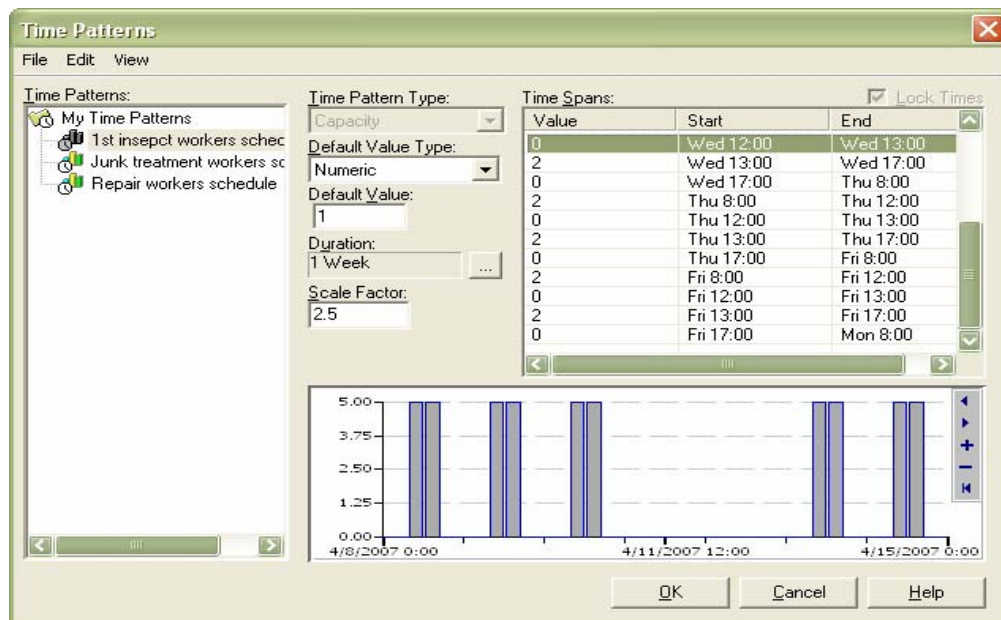


Figure 12. Time patterns in the model

Variables of each event are described below in Table 5.

Variable ID	Min value (hrs)	Mean valeur (hrs)	Max value (hrs)	Delay Type
Time_Delay 1st inspection	12	15	18	Triangle distribution
Time_Delay during Induction	28	32	40	Triangle distribution
Time_Changing_Alternative Components in Depot	15	16	17	Triangle distribution
Time_Request_for_Repair Accessory	5	-	8	Uniform distribution
Time_Work_for_Maintenance	40	48	56	Triangle distribution
Time_Final_Inspection	28	32	36	Triangle distribution
Time_Process>Loading_Vehicles _Back	16	19	22	Triangle distribution
Prob_To_Fail_1st_Inspection	0.03	-	0.05	Uniform distribution
Time_Sending_to recommendation_junk	4	5	6	Triangle distribution
Time_Publication_List_For_Induction	5	-	8	Uniform distribution
Time_Sending_To_Induction_Process	5	-	8	Uniform distribution
Prob_Excess_of_economic quality	.40	-	.50	Uniform distribution
Time_Sending to work maintenance	5	-	8	Uniform distribution
Time_Publication_List_For_Maintenance	5	-	8	Uniform

intenance				distribution
Time_Report_Work_Results	4	-	6	Uniform distribution
Time_Sending Back to work maitenance	5	-	8	Uniform distribution
Time_Sending to delivery of product	5	-	8	Uniform distribution

Table 5. Variables of CRR

This model assumes that there are two depots, CMD of ROKA and HRC as an outsource depot. We assume these two depots have approximately the same capacity, 7 or 8 K-1 TVs per month. So this model assumes that events, resources, and associated variables are the same in both depots.

3. Inventory Service Level

A depot needs Repair Parts (RP) and Spare Parts (SP) for completion of DLM of a K-1 TV. The Inventory Service Level (ISL) provides RP and SP to the depot at the right place at the right time. For efficient ISL of the depot, it should forecast the precise demand of RP and SP. It is assumed that ROK LSC plans the order schedule of RP and SP at the end of every year in the model. Among two depots, CMD and HRC, CMD only considers ISL since HRC has manufacturing plants of RP and SP of the K-1 TV. The order is sent to HRC, and it takes a substantially longer time and an additional cost to buy the parts. This model takes care of 10 kinds of RP and SP related with Figure 13 below, and assumes that variables related with the kinds of RP and SP are changed at the same range as each other.

Proportion of repair parts needed

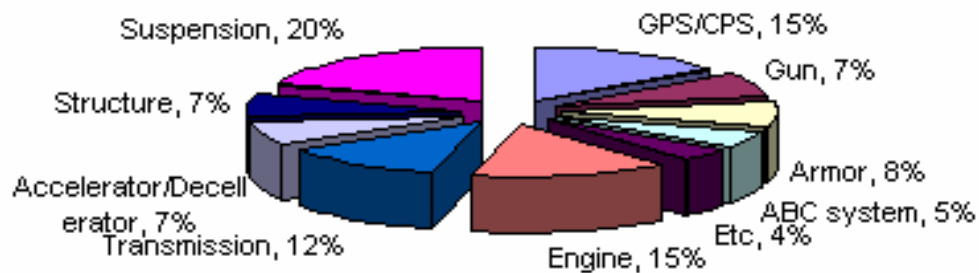


Figure 13. Proportion of repair parts needed

The lack of real data may mean this model is not realistic, but it could be extended easily if data were available.

This model contains not only quantitative variables like CFR and CRR, but also qualitative variables. Quantitative variables are the warehouse size of each RP and SP and the delays of reordering RP and SP. If the lack of RP or SP occurs, the process of DLM is stopped and waits until RP or SP become available. Table 6 lists variables of ISL in the model.

Variable ID	Min value	Mean vale	Max value	Distribution Type
Space_For_RP_and_SP (The other RP and SP are same ranges)	30EA	-	50EA	Uniform distribution
Delayed_Time_Reorder	3days	-	15days	Uniform distribution
Num_repairParts_needed	4EA		6EA	Uniform distribution

Table 6. Variables of ISL in the model

The qualitative variables specify the methodology for forecasting RP and SP demands. Several methodologies are introduced in this thesis, and they can each be qualitative variables. These methodologies are:

- Simple moving average method, and
- Weighted moving average method.

The accuracy of each methodology will be evaluated by following the process shown below in Figure 14.

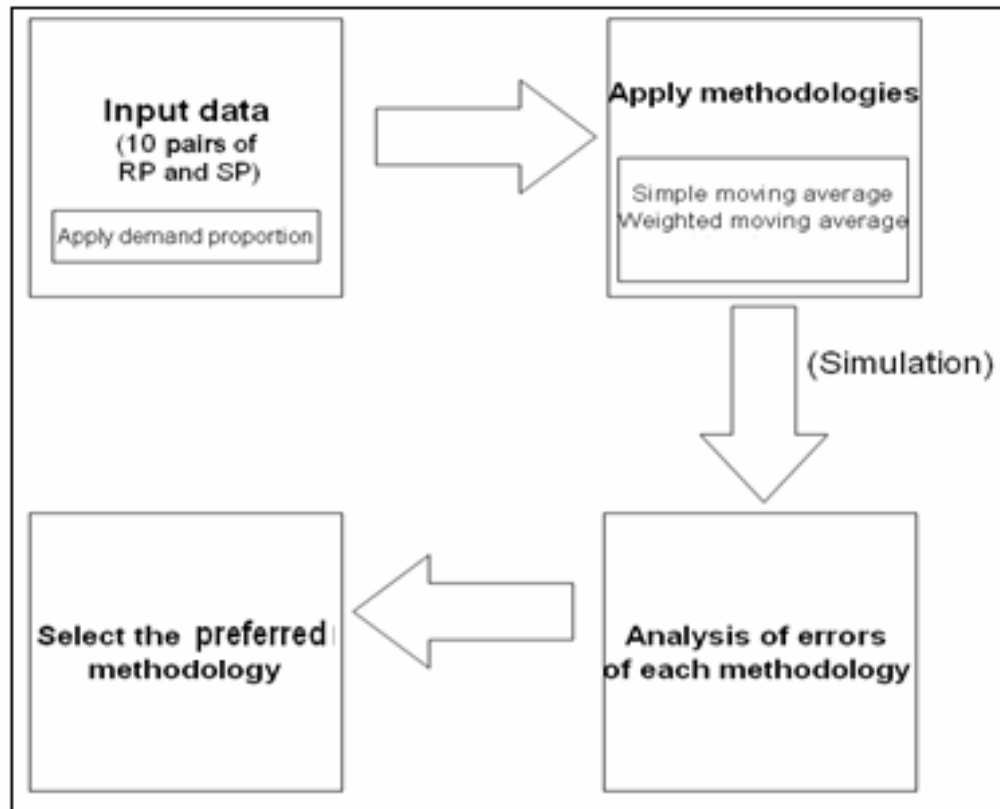


Figure 14. Process of analysis of prediction methodologies

4. Logistics Delay

Logistics Delay (LD) is the time between when a post sends a K-1 TV to the depot until it receives it back from the depot. The real world activities related to LD are simplified to construct the model.

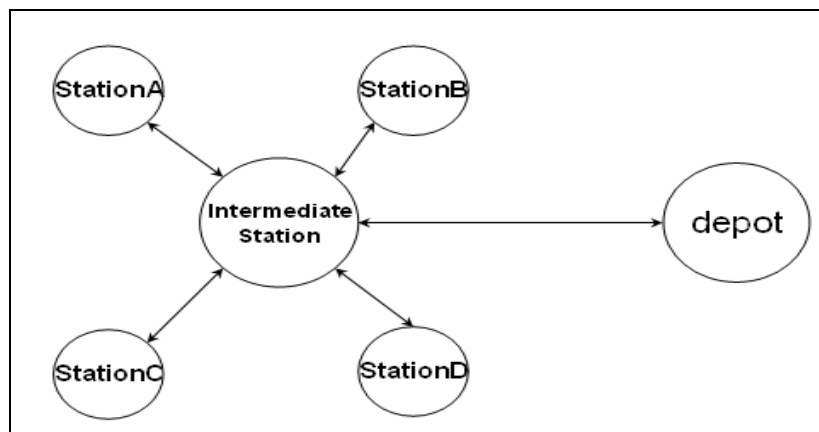


Figure 15. Railways of K-1 TV for DLM

Figure 15 shows the railways of the K-1 TV for DLM. It is assumed that there are four stations capable of loading a K-1 TV onto a Military Freight Train (MFT). The model assumes two kinds of trains, sub MFT and main MFT. The sub MFT can move between a regional station and the intermediate station, and the main MFT can move from the intermediate station to the depot. Two depots, CMD and HRC, are assumed to be at almost the same place. When the transport schedule is set, two kinds of trains are set at the same time, and it is assumed that no trains stay more than 24 hours at each station or intermediate station.

LD also considers quantitative values and one qualitative value. Quantitative values are the train schedule, each train size, the delayed time from each station to the intermediate station, the delayed time to the load K-1 TV onto the MFT, etc. Detailed descriptions of these variables appear in Table 7.

Variable ID	Min value (hrs)	Mean value (hrs)	Max value (hrs)	Delay Type
TrainSchedule	300	-	420	Uniform distribution
ReverseTrainSchedule	300	-	420	Uniform distribution
TrainSize	7 EA	-	13 EA	Uniform distribution
ProbTrailerAvailable	85%	-	95%	Uniform distribution
DelayedTime_vehicle>Loading_To_SubTrain	4	6	8	Triangle distribution

DelayedTime_vehicle>Loading_To_ReverseTrain	16	19	22	Triangle distribution
DelayedTime_FromStationA_ToIntermediateStation	1.5	-	2.5	Uniform distribution
DelayedTime_FromStationB_ToIntermediateStation	4.5	-	6.5	Uniform distribution
DelayedTime_FromStationC_ToIntermediateStation	3.5	-	4.5	Uniform distribution
DelayedTime_FromStationD_ToIntermediateStation	1.5	-	2.5	Uniform distribution
DelayedTime_Combine_SubTrains	16	19	24	Triangle distribution
DelayedTime_FromIntermediateStation_ToDepot	15	-	18	Uniform distribution
DelayedTime_Sending_to_Reverse_intermediationStation	15	-	18	Uniform distribution
DelayedTime_Process_of_Separate	16	19	24	Triangle distribution
DelayedTime_vehicle_Separating_From_SubTrain	4	6	8	Triangle distribution

Table 7. Variables of LD

One qualitative variable of LD is used to set the schedules of two depots, CMD and HRC, for DLM of the K-1 TV. Two schedules are assumed in the model.

- CMD and HRC have separate waiting lines for K-1 TVs and follow the scheduled order for DLM of the K-1 TV. Two scheduled orders are assumed in the model: one is to change the depot by the quarter; the other one is to change the depot by the semester.
- CMD and HRC share one waiting line for DLM of the K-1 TV. So, if a depot has more capability to conduct DLM, it can conduct DLM of K-1 TV.

The first scenario is close to the status quo, and the other one is a potential improvement that needs to be implemented.

D. MEASURE OF EFFECTIVENESS

To analyze the interaction of logistics elements by using a simulation model, it should be determined what output is needed for useful analysis. In this thesis, the output is a type of measure of effectiveness (MOE). A MOE is a quantitative measure, generated by a model, used to compare the effectiveness of alternatives in achieving the tactical objectives.¹⁵ The two MOEs considered in this thesis are combat readiness and readiness risk. This section will introduce the definition of these MOEs.

1. Combat Readiness

It has always been a very important issue that ROKA keeps a high level of combat readiness for weapon systems including the K-1 TV during the peacetime or wartime. The combat readiness is how ready a weapons system is for a battle, military training exercises, or other specific operations. In other words, the combat readiness refers to projected capability to meet the initial and sustained

¹⁵ T. W. Lucas, Class notes for OA 4655, Introduction to Joint Combat Modeling, Operation Research Department, Naval Postgraduate School, Monterey, CA, 2006

combat requirements of one or more specific logistics scenarios.¹⁶ These scenarios are also made up of some interactions of several logistics elements for a weapons system. This thesis describes several experiments and analysis for the effect of each logistics elements and the interaction between them to maintain the combat readiness.

There are commonly used measures of combat readiness. The most popular one is the operational availability (A_0) which is commonly observed and used in peacetime. It is expressed as

$$A_0 = \frac{uptime}{uptime + downtime} = \frac{MTBM}{MTBM + MDT}$$

where MTBM is the mean time between maintenance, and MDT is the maintenance down time (which includes repair time and administrative and logistics delay times).¹⁷

It is obvious from the formula that increasing MTBM or decreasing MDT yields a higher value of A_0 . This operational availability (A_0) is one output of the model in this thesis. The realistic readiness can project capability in explicit wartime settings, not merely describe levels of performance achieved in peacetime. It can also incorporate not only commonly measured characteristics of MTV systems, such as component reliability, but also the quantity and location of important support resources and the

¹⁶ Michael D. Rich and Stephan M. Drezner, .An Integrated View on Improving Combat Readiness, (Santa Monica, California), RAND, 1982

¹⁷ Keebom Kang, Susan M. Sanchez, and Kenneth Doerr, "A Design of Experiments Approach to Readiness Risk Analysis," Proceedings of the 2006 Winter Simulation Conference, L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nichol and R. Fujimoto, eds., pp. 1332-1339, Institute of Electrical and Electronic Engineers, Piscataway, NJ, 2006.

characteristics and performance of each important component of the support system.¹⁸

2. Readiness Risk

Readiness risk is a certain planning threshold in which there is probability that operational ready rate A_0 will remain above it.¹⁹ This measure is one of many embedded in a system used by the US Air Force for planning levels of spare parts inventory.²⁰ Readiness risk can be a important element in evaluating combat readiness, since it is true that ROKA is less concerned with the average number of mission capable K-1 TVs than they are with the probability that ROKA has enough K-1 TVs for certain military operations.

E. DESIGN OF EXPERIMENT

1. Nearly Orthogonal Latin Hypercube

There are many variables with various ranges in the model. To check all possible combinations of factor settings among all the variables with various ranges, the number of simulation runs becomes very large. It would not be possible to check every case because of constraints in

¹⁸ Michael D. Rich and Stephan M. Drezner, An Integrated View on Improving Combat Readiness, Imterim report, RAND Corp, Santa Monica, CA, 1982.

¹⁹ Keebom Kang, Susan M. Sanchez, and Kenneth Doerr, "A Design of Experiments Approach to Readiness Risk Analysis," Proceedings of the 2006 Winter Simulation Conference, L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nichol and R. Fujimoto, eds., pp. 1332-1339, Institute of Electrical and Electronic Engineers, Piscataway, NJ, 2006.

²⁰ Slay F. M., T. C. Bachman, R. C. Kline, T. J. O'Malley, F. L. Eichorn, and R. M. King, Optimizing spares support: The aircraft sustainability model. Report AF501MR1, LMI Corporation, McClean, VA, 2005.

computer resources and time. Under such a situation, a Nearly Orthogonal Latin Hypercube (NOLH) design is recommended²¹.

The Nearly Orthogonal Latin Hypercube (NOLH) is a method of designing the parameter combinations and values in order to gain nearly orthogonal correlations between parameters that are varied.²² The NOLH allows the exploration of a large number of input variables in an efficient number of runs while maintaining nearly orthogonal design columns. The greatest benefit of the NOLH is that the necessary number of simulation runs with various combinations of factors with different levels needed to fill up the parameter space is significantly smaller than traditional designs, such as a dense grid.

By the applying NOLH, many scenarios can be explored in an efficient manner. Solutions by the application of NOLH might not reveal the optimized variable settings, but they are good choices for exploring the diversity of possibilities and identifying factors and interactions that improve performance.

2. Robust Design

Robust design is a system optimization and improvement process derived from the view that a system should not be evaluated on the basis of mean performance alone. By the analysis of an acceptable mean performance, a system can be evaluated whether it is relatively insensitive to uncontrollable sources of variation present in the system's

²¹ Kleijnen, J. P. C., S. M. Sanchez, T. W. Lucas and T. M. Cioppa, A User's Guide to the Brave New World of Designing Simulation Experiments, INFORMS Journal on Computing, Vol. 17 No 3, Summer 2005.

²² Cioppa, T. and L. Brown, Agent Based Models as an Exploratory Analysis Approach to Combat Simulations, Technical Report, U.S Army TRADOC Analysis Center, Monterey, CA, 2002.

environment. The purpose of robust design is "to lead to better decisions: better in terms of implementation, better in terms of the level and consistency of performance, better in terms of cost, and better in terms of insights into the drivers of system performance."²³

Robust design leads to the following benefits:

- Fewer surprises moving from the experimental setting to real-world implementation;
- Better communication between the analyst and client via expected loss;
- Ability to evaluate trade-offs between noise reduction costs and performance quality;
- A focus on continuous improvement;
- Better decisions that can simultaneously improve performance and decrease costs;
- Representation of variability as a critical component of performance;
- Rapid model evaluation and scenario analysis
- Ability to test whether model performance is highly sensitive to parameters of input distributions used to drive the simulation model; and
- Ability to test whether component models need more detail, or whether changing a component will materially affects performance. ²⁴

²³ Susan M. Sanchez, Robust Design: Seeking the best of all possible worlds, Proceeding of the 2000 Winter Simulation Conference, Operation Research Department, Naval Postgraduate School, Monterey, CA, 2000.

²⁴ S. M. Sanchez, Class notes for OA4333: Simulation Analysis, Operation Research Department, Naval Postgraduate School, Monterey, CA, 2000.

Robust design is a great way to analyze models of complex systems because of its flexibility and efficiency. It also states important determinants of system variance. These can be used in an iterative approach to guide efforts for system improvement by conveying hidden costs to decision-makers.

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IV. DATA ANALYSIS

A. OVERVIEW

This chapter discusses the results obtained from the experiments performed for this thesis. Before the discussion of the results, the first step is to explain where and how the results came from. In brief, the input data are created by using NOLH designs, and the resulting factor settings are used for running the simulation model. The model is written in Arena 10.0 and gives the output data based on DOE. The output is written into an EXCEL spreadsheet. These data collected from DOE are analyzed by using Excel and a statistical software package, JMP. This chapter identifies significant factors and provides insight based on several critical cases. Next, various scenarios based on the methodologies to forecast demands of repair parts or to decide how to use two independent depots are presented and analyzed. Each technique is explained with the insights gained.

B. ANALYSIS OF FACTORS DRIVING PERFORMANCE

1. Experimental Design and Input Factor Settings

The output data for analysis of factors comes from an experiment that has a total of 257 scenarios, based on the factors described in Chapter II. In all, 6 factors are varied using an extremely efficient design.²⁵ To construct this design, low and high values for each factor were selected. The design then specifies a value between these two levels for each of the 257 design points.

²⁵ Keng-Ern Joshua Ang, Extending Orthogonal and Nearly Orthogonal Latin Hypercube Designs for Computer Simulation and Experiments, M.S. Thesis, Operations Research Department, Naval Postgraduate School, 2006.

For some components of the simulation model, a single factor suffices. For example, the probability of a defect resulting in the need for depot level maintenance (ProbFailures) takes on values between 0.1 and 0.15. Other components of the simulation model require more care setting up. For example, consider the input probability distribution for train schedule. In the baseline case, one random variate is generated from a uniform distribution (300, 400). In the experiment, two factors are varied to alter this distribution: the mean "TrainSchedule" and also the "TrainSchedule_spread," which ranges from a low value of 45 to a high value of 55. Other random input distributions are treated in a similar manner.

Each scenario is replicated ten times with the same input data set (but different pseudo-random number streams) for 87,600 hours of simulation time. This simulation time is equal to ten years and represents one cycle of all the K-1 TVs periodical maintenance processes. In the scenario, all of K-1 TVs are militarized during the last ten years and begin periodical maintenance at the starting point of this model.

2. Analysis of Factors Driving Performance

The basic output data consists of the operational availability, A_0 , and the quantiles of A_0 (80% less, 82%, 84%... 98%, and 100%) which represent the readiness risks. Both of output data are the average value during the simulation time, 87,600 hours. A portion of the output data is shown below in Figure 16.

Output	20												
	A	B	C	D	E	F	G	H	I	J	K	L	
1	80% less	80% to 82%	82% to 84%	84% to 86%	86% to 88%	88% to 90%	90% to 92%	92% to 94%	94% to 96%	96% to 98%	98% to 100%	Avg CR	
2	1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.16	61.68	34.59	0.98	
3	1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.22	74.01	21.20	0.98	
4	2.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.45	60.99	32.40	0.98	
5	1.59	0.00	0.00	0.00	0.00	0.00	0.00	1.10	3.34	58.27	35.70	0.98	
6	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	60.42	37.42	0.98	
7	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.46	64.71	29.24	0.98	
8	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.69	44.15	51.04	0.98	
9	1.58	0.00	0.00	0.00	0.00	0.00	0.00	0.54	2.15	54.15	41.59	0.98	
10	2.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.66	69.70	26.51	0.98	
11	1.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.81	50.89	43.71	0.98	
12	2.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	58.07	39.24	0.98	
13	1.59	0.00	0.00	0.00	0.00	0.00	0.00	0.53	5.46	63.15	29.26	0.98	
14	2.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.09	61.05	35.74	0.98	
15	1.59	0.00	0.00	0.00	0.00	0.00	0.00	0.01	9.27	57.42	31.70	0.98	
16	2.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.63	55.98	40.25	0.98	
17	1.59	0.00	0.00	0.00	0.00	0.00	0.00	1.08	1.65	59.07	36.60	0.98	
18	1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55	54.89	42.99	0.98	
19	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.18	57.60	37.11	0.98	
20	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.37	52.09	42.95	0.98	
21	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.92	63.55	30.93	0.98	
22	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.34	60.66	34.40	0.98	
23	2.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.26	57.76	37.81	0.98	
24	1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.13	59.62	36.69	0.98	
25	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.60	54.55	41.75	0.98	
26	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.57	3.91	66.89	27.03	0.98	
27	2.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.67	63.62	32.55	0.98	
28	1.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.62	68.79	28.00	0.98	
29	2.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.15	62.75	32.98	0.98	
30	1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.15	64.65	31.63	0.98	

Figure 16. Example of original output data

There are two limitations with these output data in analyzing the significant factors. The first one is that there is only slight difference between each design point such as "Avg CR" (Average combat readiness) in Figure 16. To overcome this limitation, 'total cycle time of DLM' is added as an extra output since each value of it is quite different. The second limitation is that it is impossible to directly check the accuracy of the different methodologies for forecasting repair part requirements. So, the output data that tabulates lack of each repair part is added to overcome this limitation.

L	M	N	O	P	Q	R	S	T	U	V	W
Avg CR	NumOfLack_TypeA	NumOfLack_TypeB	NumOfLack_TypeC	NumOfLack_TypeD	NumOfLack_TypeE	NumOfLack_TypeF	NumOfLack_TypeG	NumOfLack_TypeH	NumOfLack_TypeI	NumOfLack_TypeJ	Total_Time_In_Depot
0.98	19	20	10	8	9	10	14	23	16	26	1729.54
0.98	13	19	23	11	22	30	34	17	19	21	1857.95
0.98	13	6	8	17	17	17	21	14	8	16	1816.78
0.98	26	7	26	9	13	22	21	23	19	34	1902.42
0.98	26	14	16	13	6	14	5	12	11	27	1706.25
0.98	33	19	17	16	11	32	22	16	20	29	1823.39
0.98	28	13	18	16	4	23	25	16	11	21	1635.82
0.98	23	18	5	14	17	20	4	21	19	27	1751.20
0.98	73	14	27	20	11	31	13	18	22	20	1761.62
0.98	30	26	26	11	15	20	21	17	21	25	1701.08
0.98	25	12	5	8	14	21	21	11	18	35	1771.79
0.98	22	17	14	17	21	21	33	21	9	27	1977.19
0.98	13	22	19	13	14	25	20	17	15	32	1864.35
0.98	19	25	18	9	6	14	10	25	8	58	1974.00
0.98	23	17	19	12	12	18	14	7	9	25	1735.49
0.98	19	12	8	16	8	14	21	17	11	69	1740.75
0.98	18	7	17	13	19	24	20	20	10	14	1708.12
0.98	10	9	20	10	10	20	21	16	14	52	1664.63
0.98	21	18	16	5	6	13	17	19	9	33	1794.63
0.98	20	23	19	13	13	19	20	5	22	43	1799.12
0.98	28	15	14	9	13	18	19	24	17	33	1848.64
0.98	16	20	23	12	16	26	17	21	13	26	1768.17
0.98	25	17	17	12	8	16	19	15	11	23	1758.18
0.98	20	27	21	11	7	31	19	16	28	34	1734.53
0.98	31	22	18	8	11	26	24	6	20	31	1856.35
0.98	23	14	11	11	4	20	31	17	16	21	1720.79
0.98	19	19	15	17	12	29	27	22	14	33	1874.96
0.98	30	19	16	8	6	10	21	24	8	18	1766.19
0.98	25	20	15	11	13	18	20	26	18	23	1846.74
0.98	14	14	9	27	7	17	13	12	17	17	1626.62
0.98	19	18	14	12	7	22	12	17	22	31	1845.68

Figure 17. Example of extended output data

3. Regression Tree for Total Cycle Time in the Depot

The JMP partition platform provides a regression tree as a method of exploring the significant factors. It finds a series of cuts or groupings of input data that best predicts the output. It does this by exhaustively searching all possible cuts or groupings each time it prepares to make a split. These splits (or partitions) of the data are done recursively forming a tree of decision rules until the desired fit is reached.

Figure 18 presents the regression tree for the total cycle time in the depot. The first split indicates that when the train schedule from the depot to each post after the maintenance process, defined as "Back_TrainSchedule" in the regression tree, is greater than or equal to 364.22, there are 1,689 cases among 2,570 total cases in this condition, and the total cycle time tends to be higher than

the overall average. On the other hand, when "Back_TrainSchedule" is less than 364.22, there are 881 cases in this condition and the mean value tends to be lower than the overall average. The second and the third splits in the tree show the significance of the train schedule from each post to the depot, defined as "TrainSchedule" in the regression tree. Between the values of 369.38 and 346.41, the output values are partitioned. Simply stated, the total cycle time for the scenarios examine is mostly affected by "Back_TrainSchedule" and "TrainSchedule."

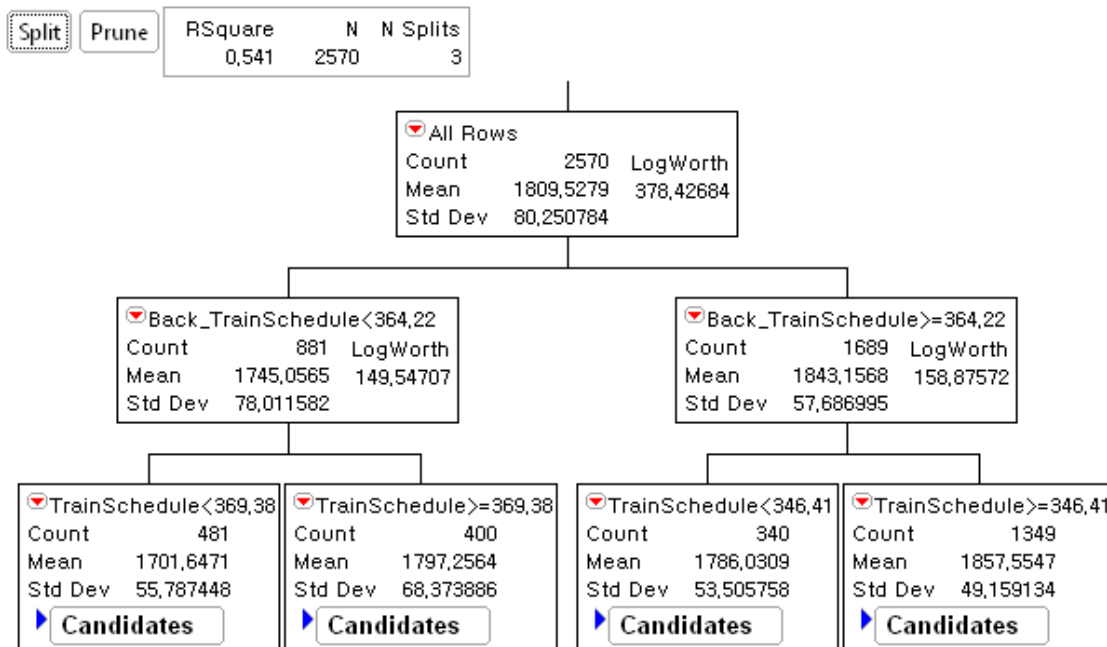


Figure 18. Regression Tree for Total Cycle Time

By splitting the output data until achieving the desired fit, this regression tree is able to show the significance of factors. Since the regression trees assume no specific distributions and parameters, they are very useful for exploring relationships when the analyst does not have a good prior model. They handle large problems

easily, and the results are very interpretable. However, there are some limitations in using regression trees. It may be necessary to figure out the relative importance of factors that appear in different places on the tree, or how much the interaction of each important factor affects the output. It is better for description of a data set than for predicting performance at other, untried factor values. For these reasons, regression trees are often supplemented with other techniques.

For example, "Back_TrainSchedule" is the factor in the first split of the regression tree. It means that if we decrease the mean time of trains that transport K-1 TVs from the depot to the intermediate station, the total cycle time will be substantially decreased. However, if this case is considered in common sense, it cannot always be true. If ROKA LSC minimizes the train schedule as much as they possibly can, it just leads to very inefficient schedules unless the K-1 TVs are ready to be transported from the depot to their own post. On the contrary, even if the train schedule from each post to the depot increases the number of trains as much as possible, this will not yield substantial improvements in the total cycle time if the repair rate of the depot does not change and does not adapt to match the train schedule.

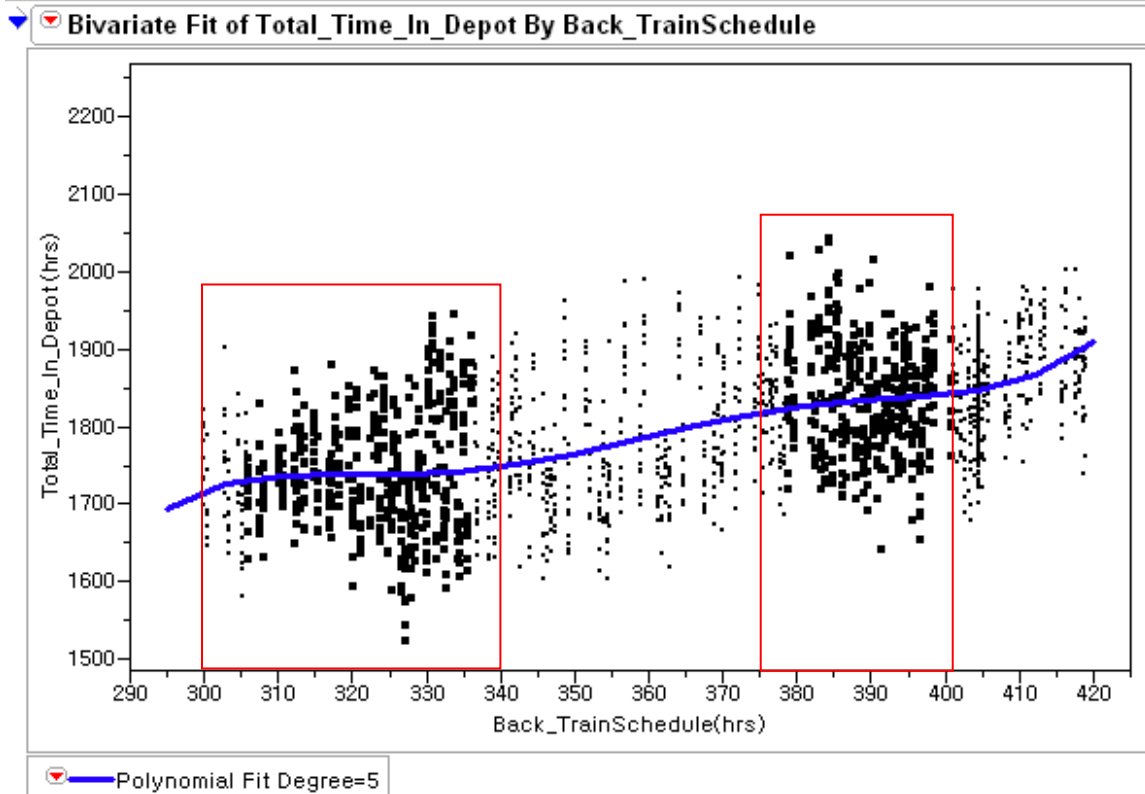


Figure 19. Bivariate Fit of Total_Time_In_Depot By "Back_TrainSchedule"

The plot shown in Figure 19 is the polynomial fit of degree = 5 within the range of (300, 420). The overall distribution of each design point looks as though the total cycle time is decreased as the time of "Back_TrainSchedule" is decreased. However, there does not appear to be a decline in the ranges of (300, 340) and (380, 400). In the range of (380, 400), there are other factors or interactions that affect the total cycle time more strongly and with less interaction of decreasing the "Back_TrainSchedule". In the range of (300, 340), the "Back_TrainSchedule" has less affect on the results than any other range, and is considered the inefficient range as previously mentioned above.

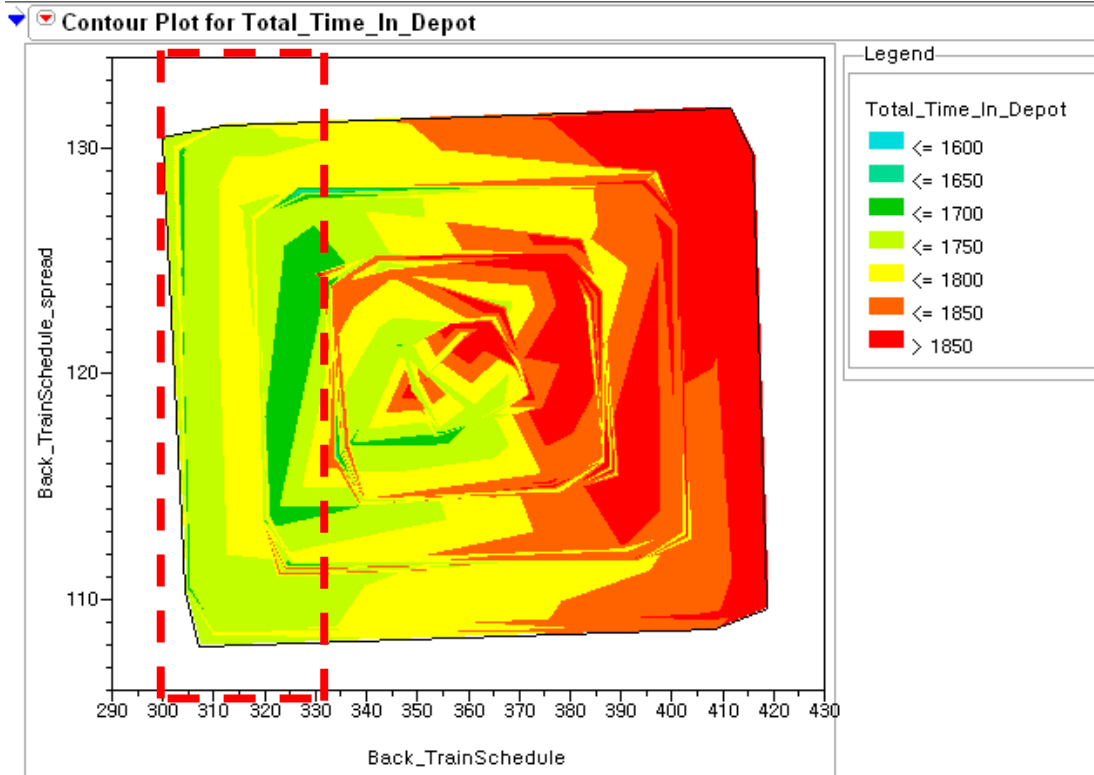


Figure 20. Contour Plot for Total_Time_In_Depot

Figure 20 shows another example of the interactions of factors desired to affect the results. In the model, the train schedule from the depot to an intermediate station is defined to follow a uniform distribution with the range of ("Back_TrainSchedule", "Back_TrainSchedule" + "Back_TrainSchedule_spread"). In general, it shows that as the number of trains of "Back_TrainSchedule" increases and "Back_TrainSchedule_spread" tends to be more increasing of the total cycle time. However, the summation of high values of "Back_TrainSchedule" with low values of "Back_TrainSchedule_spread" also shows a large distribution of high values of the total cycle time. It shows the total cycle time is not affected from "Back_TrainSchedule". It also shows that the minimum value of each factor cannot yield the maximum result. "Back_TrainSchedule" in the

dashed red box shows that decreasing both factors does not affect the results very much. More numerical analysis will be discussed in the multiple regression analysis section.

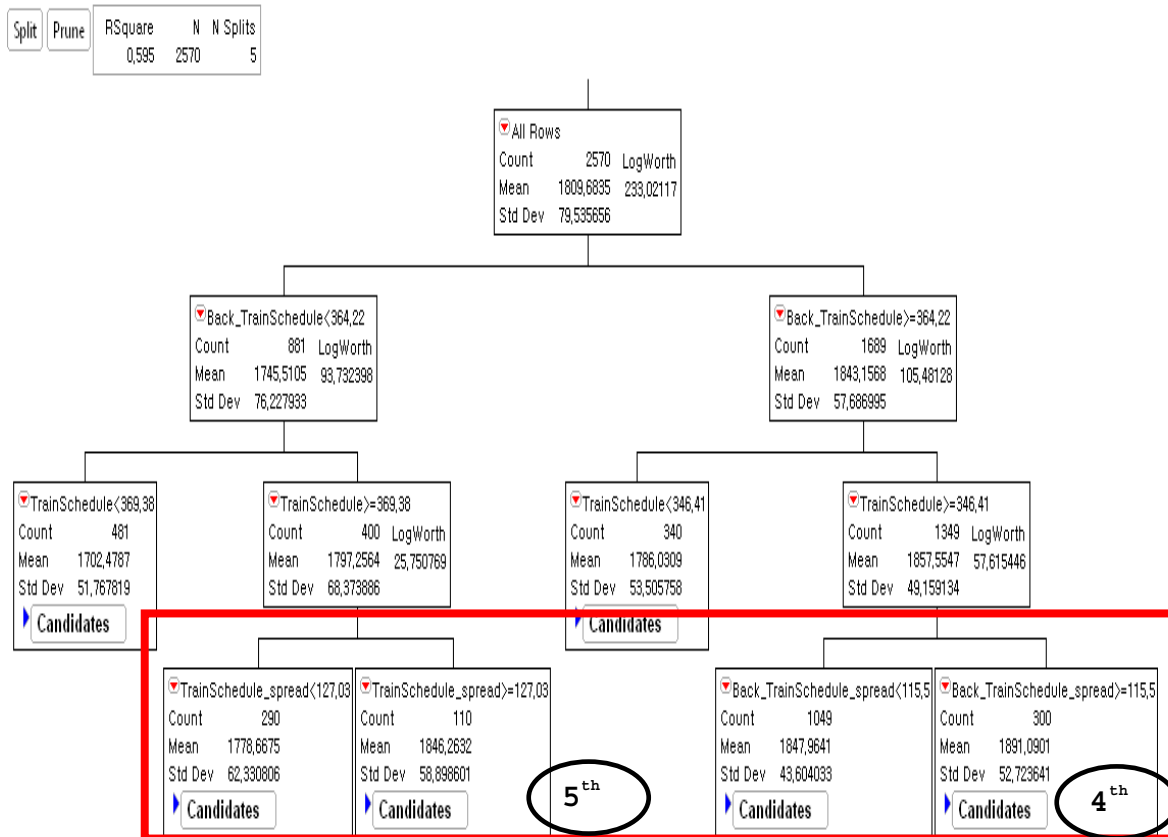


Figure 21. The 4th and 5th splits of regression tree

The red box of Figure 21 illustrates an interaction. Between the 4th and 5th splits, the factors in each case are different. This explains that the importance of factors can be affected by the conditions of factors. For example, when "Back_TrainSchedule" <364.22 and "TrainSchedule" ≥ 369.38 then the "TrainSchedule_spread" has a greater effect on the total time in the depot than "Back_TrainSchedule_spread". More detailed interaction analysis is also discussed in the next section using a regression modeling approach.

4. Multiple Regression Analysis

Multiple regression is a technique to determine the effect of diverse factors on a response variable. It applies linear combinations of coefficients of factors that predict the response variable by minimizing the mean square error (MSE). In this analysis, the main factors that affect the result can be considered, along with quadratic and two-way interaction terms involving the main factors.

a. Main Effects Model

The analysis starts to find what factors mainly affect the results. The total cycle time in the depot is selected as the response factor, and the sixty-six input factors are considered potential explanatory factors. In this analysis, stepwise regression is used to find main factors.

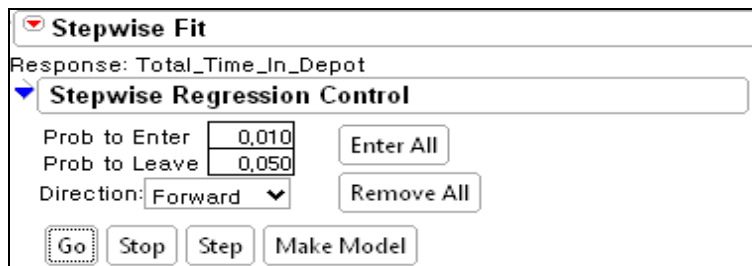


Figure 22. Stepwise regression control panel

This technique gives a stepwise regression for a single continuous or categorical response and all types of effects. This analysis assumes that the significance probability that must be attributed to a regressor term entering into the model is 0.010 or less, and that a regressor term will be removed from the model if its significance level is 0.050 or more. The exception is that main effects will be retained as long as an interaction or quadratic effect is in the model. The entering and exiting criteria are shown above in Figure 22.

The step history, leading to a main effects model involving 16 main factors, is displayed below in Table 8.

Step	Parameter	RSquare
1	Back_TrainSchedule	0.3414
2	TrainSchedule	0.5171
3	TrainSize_spread	0.556
4	TrainSize	0.5841
5	TrainSchedule_spread	0.5965
6	Time_Final_Inspection	0.6039
7	Num_repairParts_needed	0.6091
8	Back_TrainSchedule_spread	0.6137
9	Time_Publication_List_For_Maintenace	0.6171
10	Num_repairParts_needed_spread	0.6202
11	Prob_To_Fail_1st_Inspection_spread	0.6228
12	T_changelnDepot_spread	0.6258
13	Time_Process>Loading_Vehcles_Back	0.6275
14	Time_Sending to work maitenance_spread	0.6287
15	Time_Sending_to_Original_Place_spread	0.6303
16	Time_vehicle_Seperating_From_SubTrain	0.6313

Table 8. Step history of main factors

The next step is to perform a standard least squares regression on the selection for finding a least square fit and analysis of variance tables.

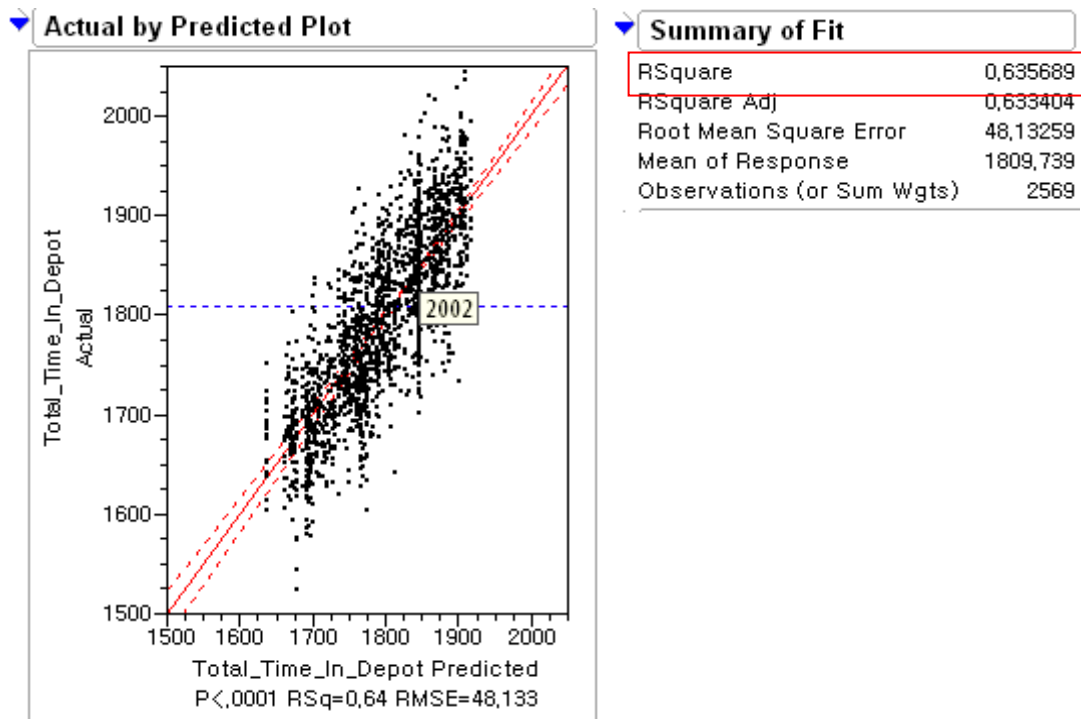


Figure 23. Actual by predicted plot for Total_Time_In_Depot with main effect factors

Figure 23 shows that the R-Square value is 0.636 on the selected sixteen factors. The significance level, or p-value, associated with each selected factor is less than 0.0001 except for three factors: "Time_Sending_to_work maintenance_spread" generates a p-value of 0.0005, "Time_Sending_to_Original_Place_spread" generates a p-value of 0.0007, and "Time_vehicle_Seperating_From_SubTrain" generates a p-value of 0.0092. These results show that the sixteen factors are significant at any significance level greater than 0.0092.

b. Two-way Interaction and the Quadratic Model

In this analysis, the interactions of factors are considered for further investigation within the data. The analysis is performed by using the "factorial to degree 2" macro to add interaction effects as potential explanatory terms. The same probabilities to enter and leave are used,

which are 0.01 and 0.05 respectively. Once the important terms have been identified, the next step is to conduct stepwise regression and a standard least squares regression as was done for the main effect model.

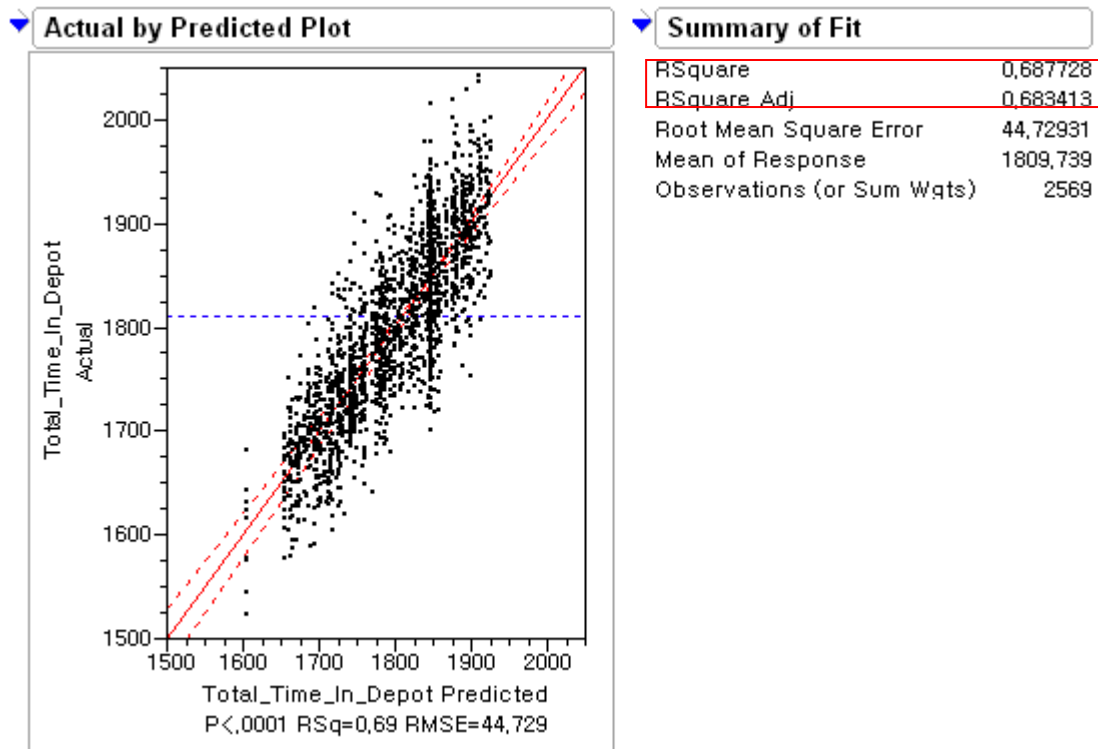


Figure 24. Actual by predicted plot for Total_Time_In_Depot With main effect factors and two-ways interactions

Figure 24 shows that the R-square value is 0.688 and contains a total of thirty-five terms that include twenty main effect factors and fifteen interactions. Twelve terms have a significance level less than 0.0001, fourteen terms have a significance level between 0.1 and 0.0001, and nine terms have a significance level greater than 0.1. This result explains that some of the terms are significant at any significance level, but the other ones are not so significant. Since the number of terms is still too large to consider all of the possible interactions, that number needs to be reduced to find the main interactions.

In this analysis, the quadratic model combines main effect factors, interaction terms, and polynomial terms. It employs exactly the same techniques and the same probabilities of entering and leaving in the two-way interaction model.

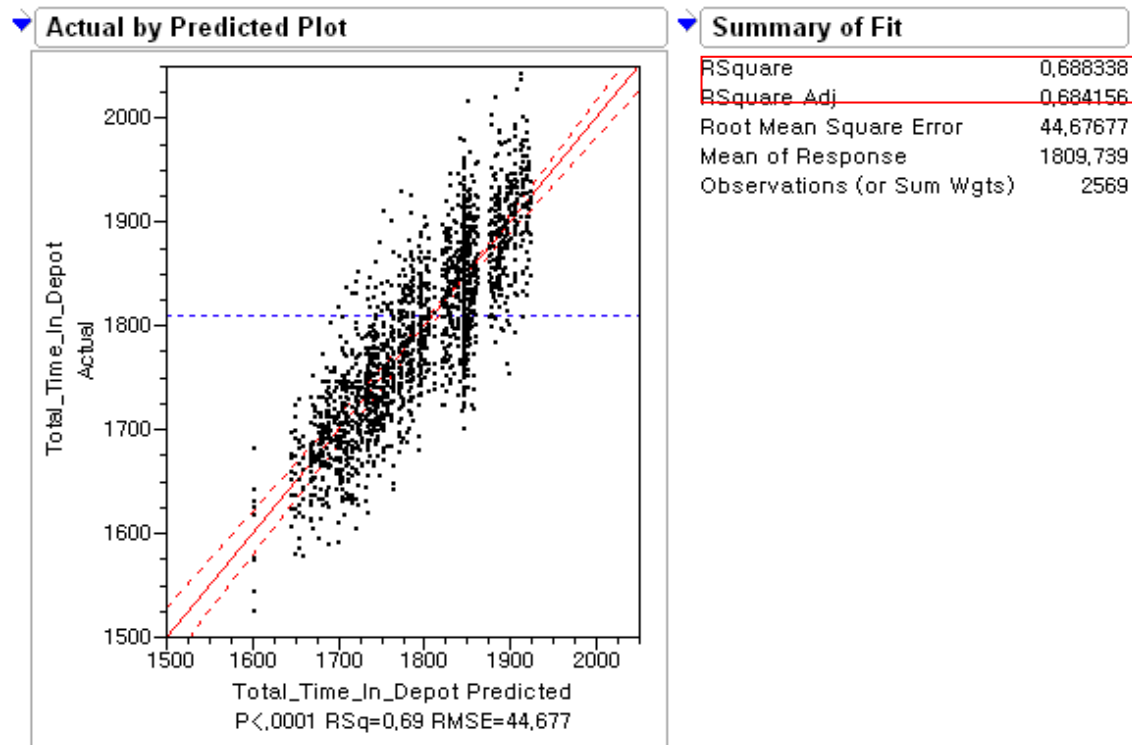


Figure 25. Actual by predicted plot for Total_Time_In_Depot
With main effect factors, two-ways interactions of them,
and polynomials

Figure 25 shows that the R-square value is 0.688. In this quadratic model, the stepwise process generates thirty-four terms, including nineteen main effect factors, thirteen interaction terms, and two polynomial terms. Sixteen terms have significance levels less than 0.0001, fourteen terms have a significance level between 0.1 and 0.0001, and four terms have a significance level greater than 0.1. This is similar in its complexity and its overall fit to the model with interactions. However, it still has

too many terms to analyze all the possible interactions and the number of terms needs to be minimized.

c. Evaluating Final Regression Model Results

The step history of the quadratic model ought to be considered in order to develop a final model that has enough numbers of terms within the reasonable R-square value. Table 9 shows the step history of fifteen significant terms in the quadratic model and shows the significant terms with their R-square value in the model.

Step	Parameter	RSquare
1	(TrainSchedule-368.193)*(Back_TrainSchedule-375.232)	0.5406
2	(TrainSize-7.18801)*(TrainSize_spread-5.99221)	0.604
3	(TrainSchedule_spread-119.362)*(TrainSchedule_spread-119.362)	0.6221
4	(Num_repairParts_needed_spread-1.94026)*(TrainSize_spread-5.99221)	0.6392
5	(Time_Final_Inspection-31.1022)*(Back_TrainSchedule_spread-117.453)	0.6488
6	(TrainSize-7.18801)*(TrainSize-7.18801)	0.6563
7	(probAge-0.10123)*(TrainSize-7.18801)	0.6643
8	(Num_repairParts_needed-3.96069) *(Time_FromNodeA_ToIntermediateStation_spread-0.51699)	0.6701
9	(Prob_To_Fail_1st_Inspection_spread-2.0574) *(Time_vehicle_Loading_To_SubTrain_spread-1.94538)	0.6751
10	(TrainSchedule-368.193)*(TrainSize-7.18801)	0.6784
11	(Time_Sending to work maintenance-6.07218) *(TrainSchedule_spread-119.362)	0.6813
12	(Time_Work_for_Maintenance-46.8523) *(Time_Sending Back to work maintenance_spread-2.9672)	0.6836
13	(Time_WM_spread-8.16009) *(Time_FromNodeA_ToIntermediateStation_spread-0.51699)	0.6855
14	(TD_insp1_spread-3.06062)*(Time_Final_Inspection-31.1022)	0.687
15	(Time_Sending_to recommendation_junk-4.94642) *(Num_repairParts_needed-3.96069)	0.6883

Table 9. 15 significant terms of the quadratic model with R-square value

Table 9 shows two polynomial terms and thirteen interaction terms, but no main effect factors only (although main effects will be added automatically if an interaction or quadratic term is added). This indicates that every interaction and quadratic effects must be considered.

Figure 26 shows the response R-square values that result at each step.

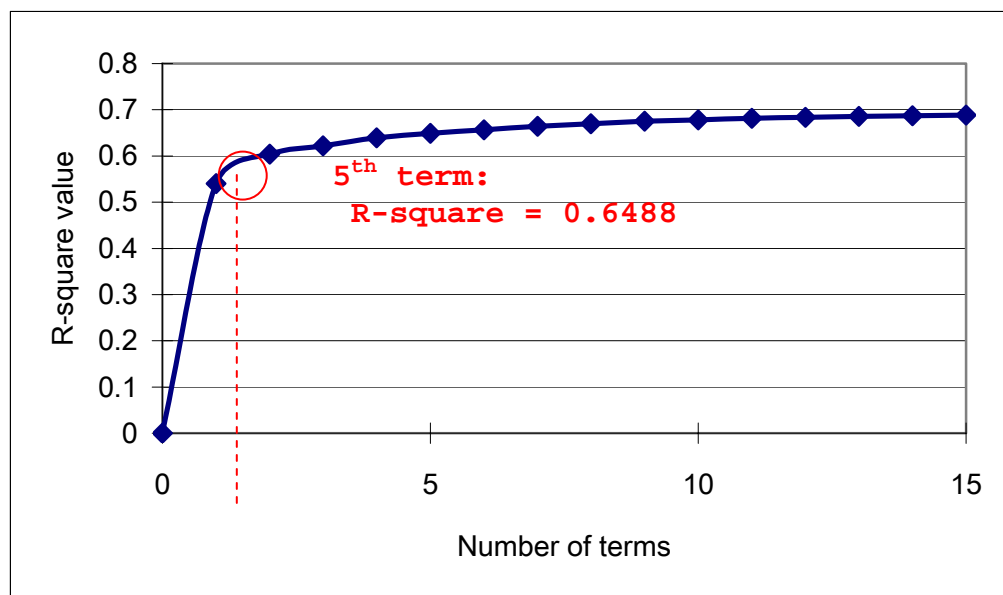


Figure 26. Number of terms versus R-Square values in the quadratic model

As shown by the value of the 5th term, the subsequent values do not differ from each other and show a flattening trend. So, it is still reliable to cut off the extra terms after the 5th step and to consider the 1st through 5th terms. These terms consist of four interaction terms, one quadratic term, and the associated main effects. The relationship between the terms and the output data are displayed below in Figure 27.

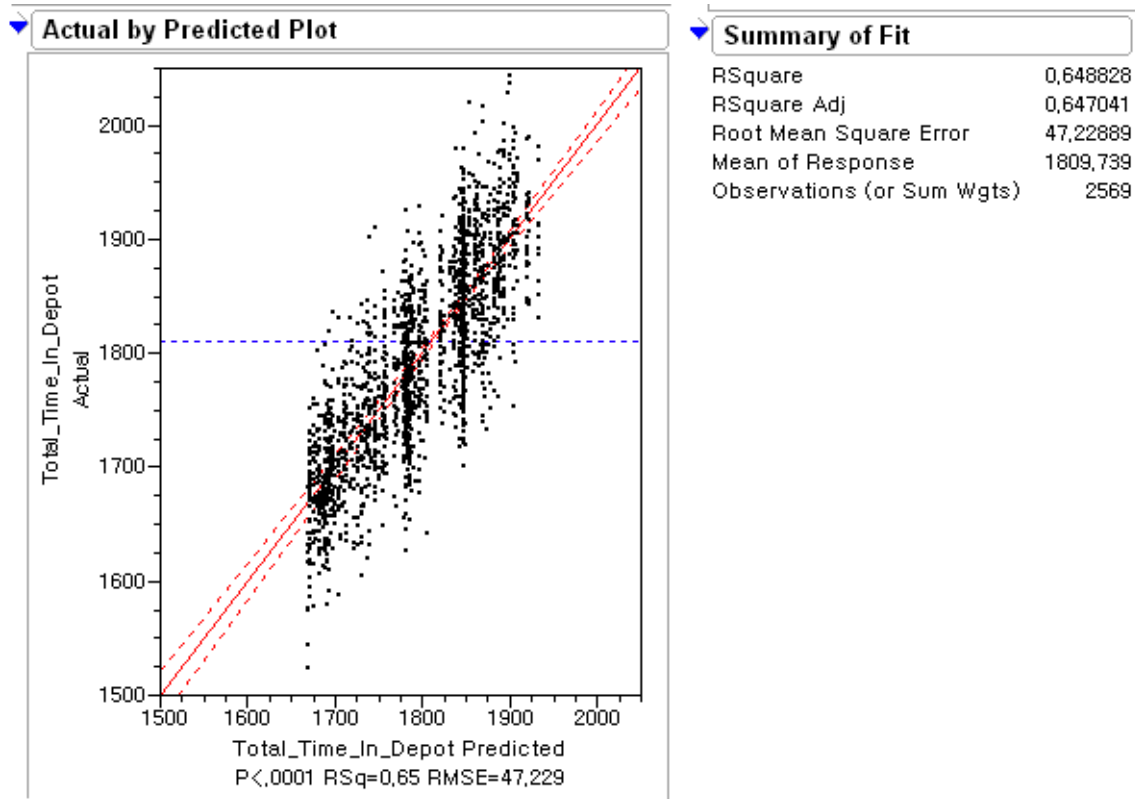


Figure 27. Actual by predicted plot of the final model

Since the R-square value is 0.649 and close to the R-square value of fifteen terms, the factor profiler and the interaction profiler that introduced at the next section are based on this standard least square model.

d. Factor Profiling

The factor profiler displays a prediction trace for each input factor. A prediction trace is the predicted response as one variable is changed while all others are held constant at the current values. The Prediction Profiler in JMP recomputes the traces and predicted responses as varying the value of each factor.²⁶

²⁶ JMP 6.0.0 Manual: Statistics and Graphic Guide: Standard Least Squares: Exploring the Prediction Equation.

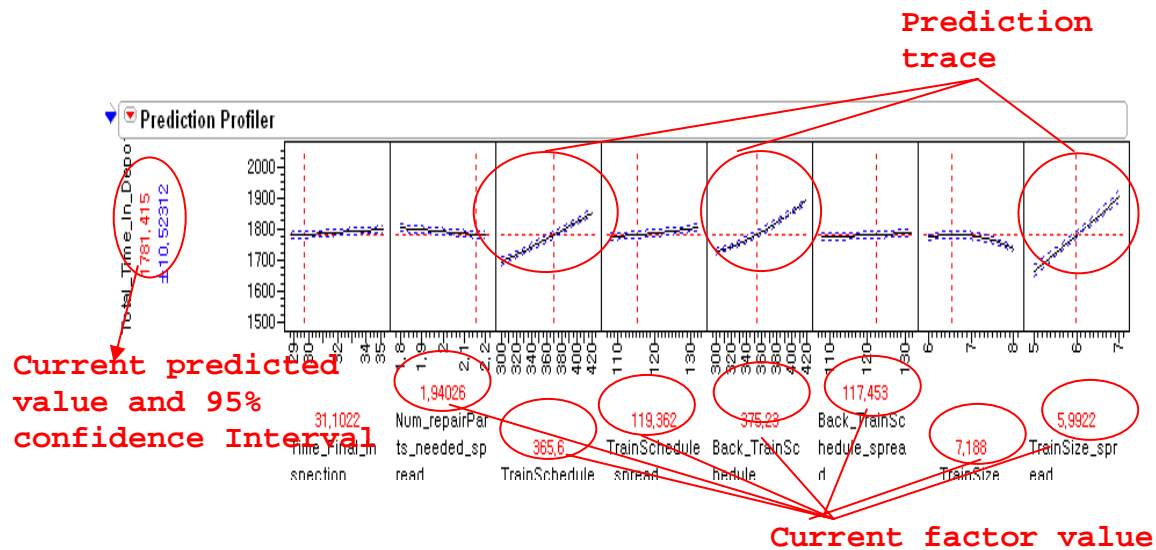


Figure 28. Prediction Profiler of main effect factors

The illustration in Figure 28 describes the current predicted value of "Total_Time_In_Depot" for the current values of the main effect factors. The slope and markers show how the predicted value changes the current values of an individual main effect factor.

The prediction trace slopes in red circles show that the predicted value has a quite strong positive relationship with the main effect factors of "Train_Schedule", "Back_Train_Schedule", and "TrainSize_sread". In other words, the trace of these factors is more valuable than the trace of other factors because they have strong relationship with "Total_Time_In_Depot".

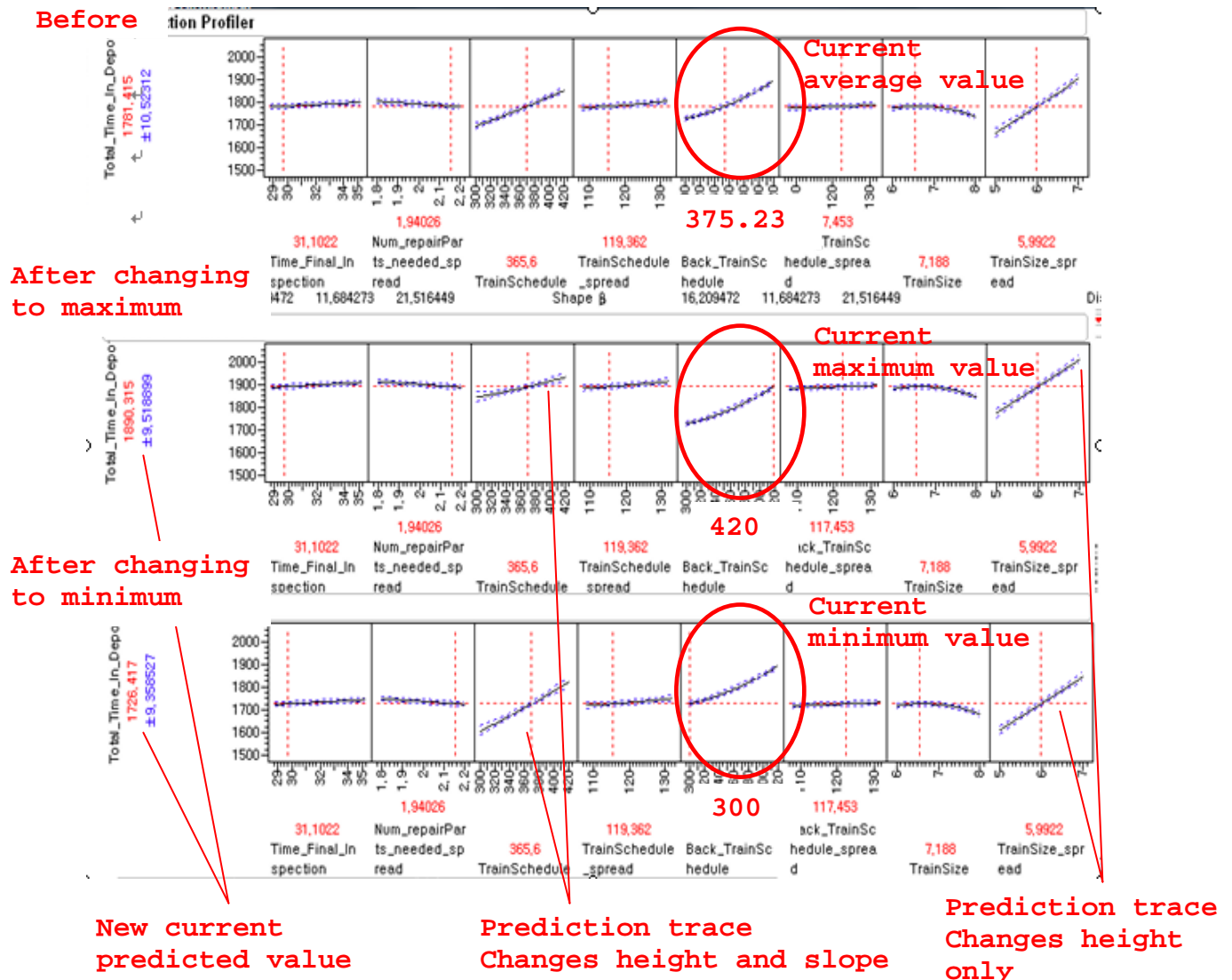


Figure 29. Changing "Back_TrainSchedule" to maximum and minimum value

"Back_TrainSchedule" is changed from an average value to the maximum and minimum values in Figure 29. It describes whether the factor changing the value for analysis is important or not by observing the change of the predicted value. Figure 29 shows the predicted value is 1890.315 ± 9.518 when "Back_TrainSchedule" has the maximum value and 1726.417 ± 9.356 when "Back_TrainSchedule" has the minimum value. A variation of almost 10% of the total cycle time can be observed by changing "Back_TrainSchedule"

only. This shows how significant "Back_TrainSchedule" is. The importance of other factors can be also assessed to some extent by the steepness of their prediction traces.

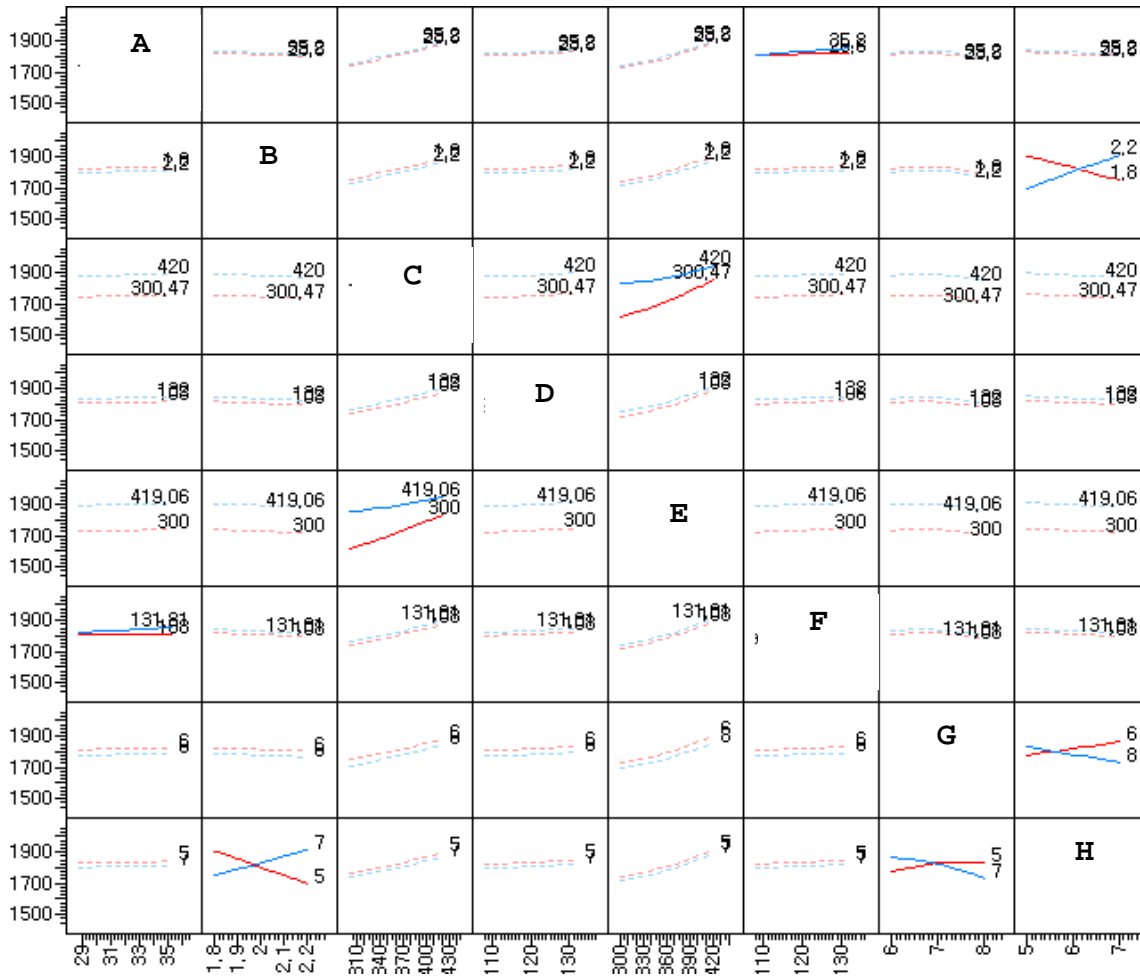
This prediction profile is also able to show whether factors interact with each other or not. When a factor's value is changed, the prediction traces of all other factors also changed. If there are interaction effects (sometimes called cross-product effects) in the model, changing the current value of one factor means the prediction traces for other factors can shift their slopes and curvatures. If there are no interaction effects, the traces only change in height, not slope or shape.²⁷ In Figure 29, the prediction trace of "TrainSchedule" shifts its slope and height by changing "Back_TrainSchedule", but "TrainSize_spread" just shifts its height. So, it is possible to say that "TrainSchedule" has interaction with "Back_TrainSchedule" and "TrainSize_spread" has little interaction with "Back_TrainSchedule".

e. Interaction Profiler

The interaction profiler is also a good technique to analyze interactions of factors. It introduces interaction plots that are interactive with respect to the profiler values. This option can help visualize third degree interactions by seeing how the plot changes as current values for the terms are changed.²⁸

²⁷ JMP 6.0.0 Manual: Statistics and Graphic Guide: Standard Least Squares: Exploring the Prediction Equation

²⁸ JMP 6.0.0 Manual: Statistics and Graphic Guide: Standard Least Squares: Exploring the Prediction Equation: Interaction Plots



A	Final_Inspection_Time	E	Back_TrainSchedule
B	Num_repairParts_needed_spread	F	Back_TrainSchedule_spread
C	TrainSchedule	G	TrainSize
D	TrainSchedule_Spread	H	TrainSize_spread

Figure 30. Interaction Profilers of main effect factors

Figure 30 shows the interaction profile plot for the final model. The y-axis represents total cycle time in the depot and x-axis is the range of each factor. As the absolute value of the slope of the column term increases, the significance of the column factor also increases. The gap between the lines corresponding to the maximum value and the minimum value of each box also shows the

significance of the row factor. The interaction is shown when the shift of the slope or shape has occurred.

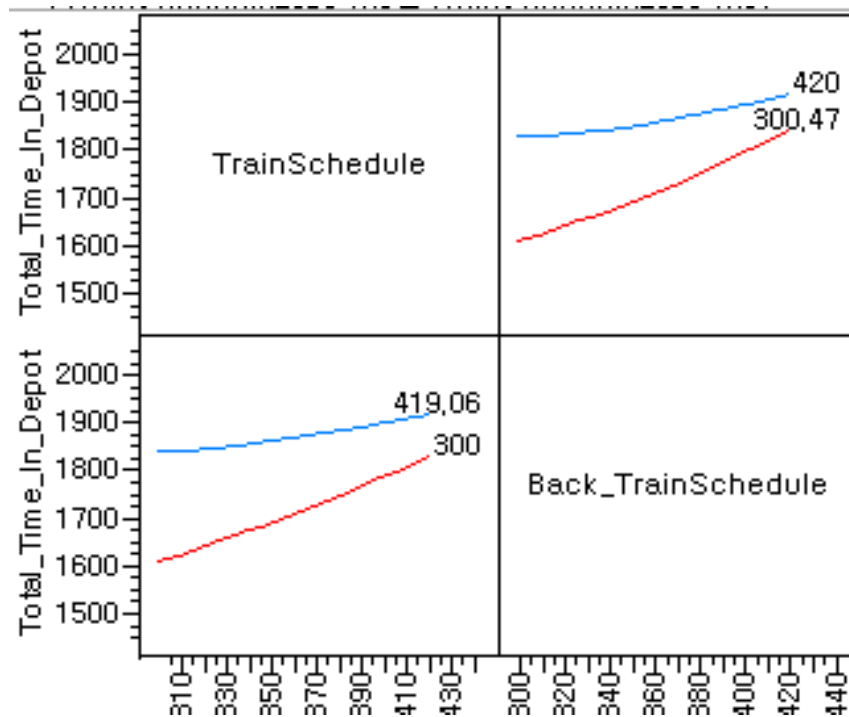


Figure 31. Interaction Profiler Plots of "TrainSchedule" and "Back_TrainSchedule"

Figure 31 shows the example of the interaction of two factors. The first thing to note is the shift of the slope between the maximum and minimum values. When "TrainSchedule" has the minimum value, the change of "Back_TrainSchedule" affects the "Total_Time_In_Depot" more strongly. This means that the significance of "Back_TrainSchedule" depends on "TrainSchedule". In other words, when the smallest number of trains from each post to the depot is scheduled, the control of the train schedule from the depot to each post can noticeably decrease the total cycle time.

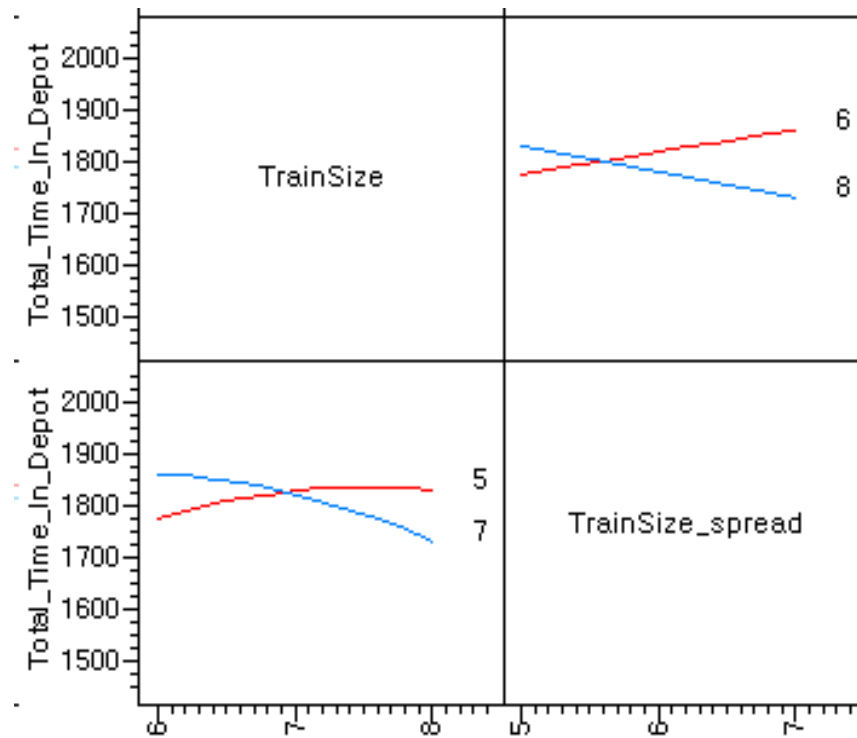


Figure 32. Interaction Profiler between "TrainSize" and "TrainSize_spread"

Figure 32 shows another example of interactions of factors. First of all, the curvature form of the slope of "TrainSize_spread" indicates that the quadratic effect of "TrainSize_spread" occurs as a result. When "TrainSize" is six, increasing "TrainSize_spread" yields a positive effect on the result. On the contrary, when "TrainSize" is eight, increasing "TrainSize_spread" yields a negative effect on the result.

Other interactions of interest can be analyzed by following this same process. Since the prediction profiler in JMP can change the factor values, it is also beneficial to check the interaction plots with changing factors by using the prediction profiler.

C. SCENARIO COMPARISONS AND INSIGHTS

1. Overview of Scenarios

In order to compare scenarios, the exact scenarios need to be defined. Basically, scenarios were defined by the classification of qualitative variables in the experiment. The qualitative variables are outlined below in Table 10.

Inventory Service Level (Forecasting methodologies)	Weighted moving average method
	Simple moving average method
Logistics Delay (Changing depot schedules)	Quota K-1 TV per semester
	Quota K-1 TV per quarter
	Quota K-1 TV by checking the queue (finding smallest queue)

Table 10. Outlines of scenarios in the experiment

The purposes of these scenarios are to compare the efficiency of different forecasting methods for the demand of repair parts, as well as to compare the assignment of work to one of the two depots, ROK CMD or HRC.

In the experiment, the 257 design points defined by using NOLH are applied to each scenario without any replications. The equations of the forecasting methodologies are defined below in Table 11.

Simple Moving method	Weighted Moving method
$Y_t = \frac{\sum_{i=1}^n A_{t-i}}{n}$ <p>Y_t :Forecast demands for the t^{th} time period</p> <p>A_{t-i} : Actual demands of the $(t-i)^{th}$ time period</p> <p>n: number of time periods involved</p>	$Y_t = \frac{\sum_{i=1}^n W_{t-i} A_{t-i}}{n}, \quad W_{t-i} = n_{t-i}$ <p>Y_t :Forecast demands for the t^{th} time period</p> <p>W_{t-i} : Weight value for the $(t-i)^{th}$ time period</p> <p>A_{t-i} : Actual demands of the $(t-i)^{th}$ time period</p> <p>n: number of time periods involved</p>

Table 11. Equations of the forecasting methodologies

The ways to allocate work to one of the two depots are separated into three ways, like in Table 10, and are compared to each other with MOEs.

2. Measure of Effectiveness Comparison

There are two MOEs, combat readiness and readiness risk. Combat readiness is measured by using the operationally ready rate:

$$A_0 = \frac{uptime}{uptime + downtime} = \frac{MTBM}{MTBM + MDT}.$$

Readiness risk is a certain planning threshold in which the probability that the operational ready rate A_0 will

remain above it.²⁹ The comparisons of MOEs are conducted by separating into the forecasting methodologies and the changing depot schedules.

a. Comparison of Forecast Average

The scenario of the simple moving method will be referred to as "Scenario 1," and the scenario of the weighted moving method will be referred to as "Scenario 2". The total cycle time results for each methodology are displayed in Figure 33.

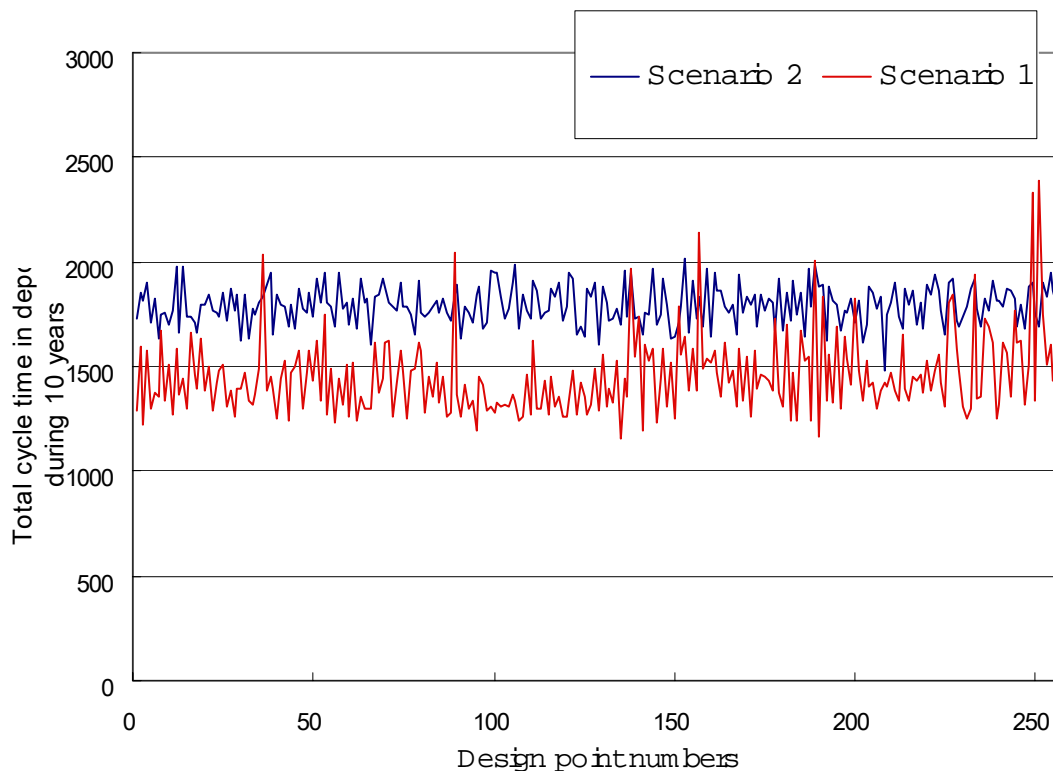


Figure 33. Plot of the distribution of the total cycle time

In Figure 33, it appears that "Scenario 1" almost always yields a shorter total cycle time than does "Scenario 2". In this case, it is easy to compare two

²⁹ Keebom Kang, Susan M. Sanchez, and Kenneth E. Doerr, A Design of Experiments Approach to Readiness Risk Analysis for Performance Based Logistics, Technical Report, Graduate School of Business & Public Policy, Naval Post Graduate School, Monterey, CA, September 2006

scenarios since the difference between them is so definite. However, there needs to be a more accurate comparison if the distribution between them is not so clear. For a more accurate comparison, a paired t-test can be applied.

The first hypothesis test is defined as a two-tailed test. The null hypothesis assumes that there is no difference between the mean values of the two scenarios. Then the hypothesis test is conducted below:

$$H_0: \mu_1 - \mu_2 = 0$$

$$H_1: \mu_1 - \mu_2 \neq 0$$

\bar{d} = the mean of difference, s^2 = the sample variance,

n = the sample size,

$$t = \frac{\bar{d}}{\sqrt{s^2/n}} = \frac{357.332}{\sqrt{21544.042/257}} = 39.027 \text{ with } n-1 \text{ degree of freedom}$$

$$p\text{-value} = 2 \times \{\min(P(t \leq 39.027), P(t > 39.027))\} \leq 0.0001$$

Since $p\text{-value} \leq 0.0001$ is very small and gives a very small significance level α , H_0 is rejected. This means that there is a statistically significant difference between two scenarios. A 95% confidence interval for the difference $\mu_1 - \mu_2$ is (339.39, 375.28). It can be concluded that "Scenario 1" yields a better result than "Scenario 2".

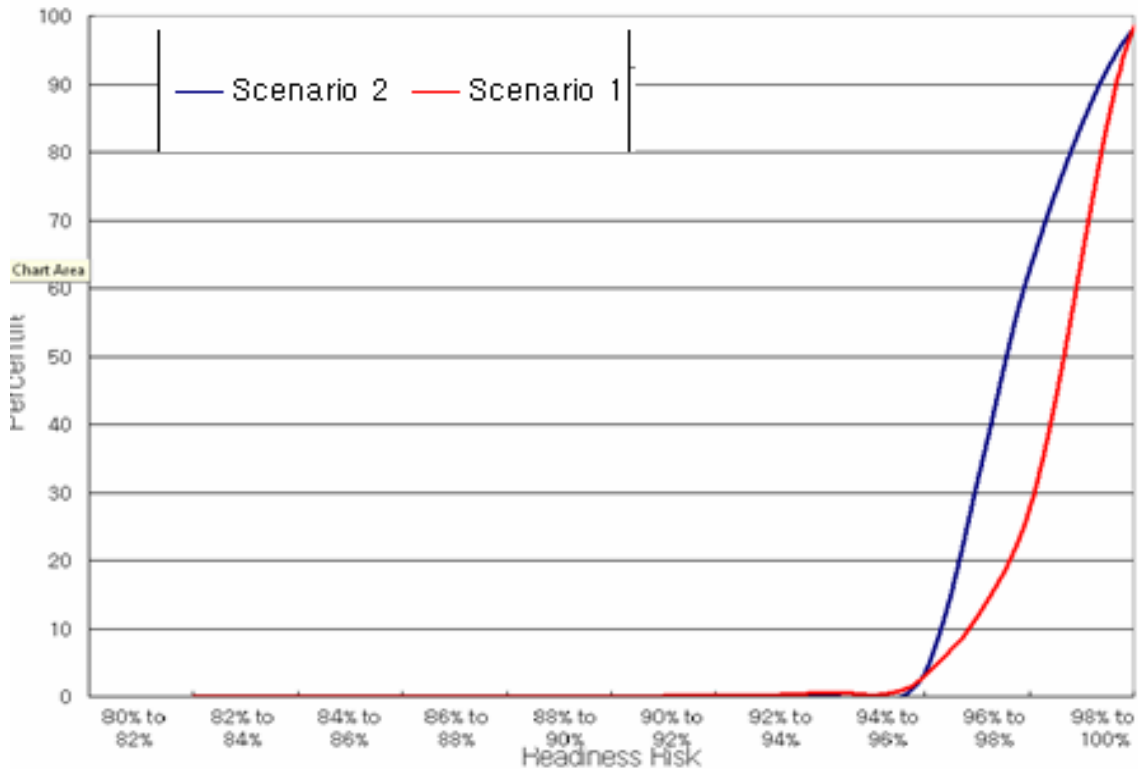


Figure 34. Cumulative curves of the readiness risk of each scenario

Figure 34 displays the cumulative percentile of readiness risk of each scenario. At "98% to 100%", the cumulative percentiles of both scenarios reach 100 percent. But the cumulative percentiles at "96% to 98%" are 60 percent for "Scenario 2" and 25 percent for "Scenario 1". This means that the proportion of time high combat readiness is achieved is larger for "Scenario 1" than for "Scenario 2". So, the comparison of readiness risk also shows the same conclusion with the comparison of the total cycle time.

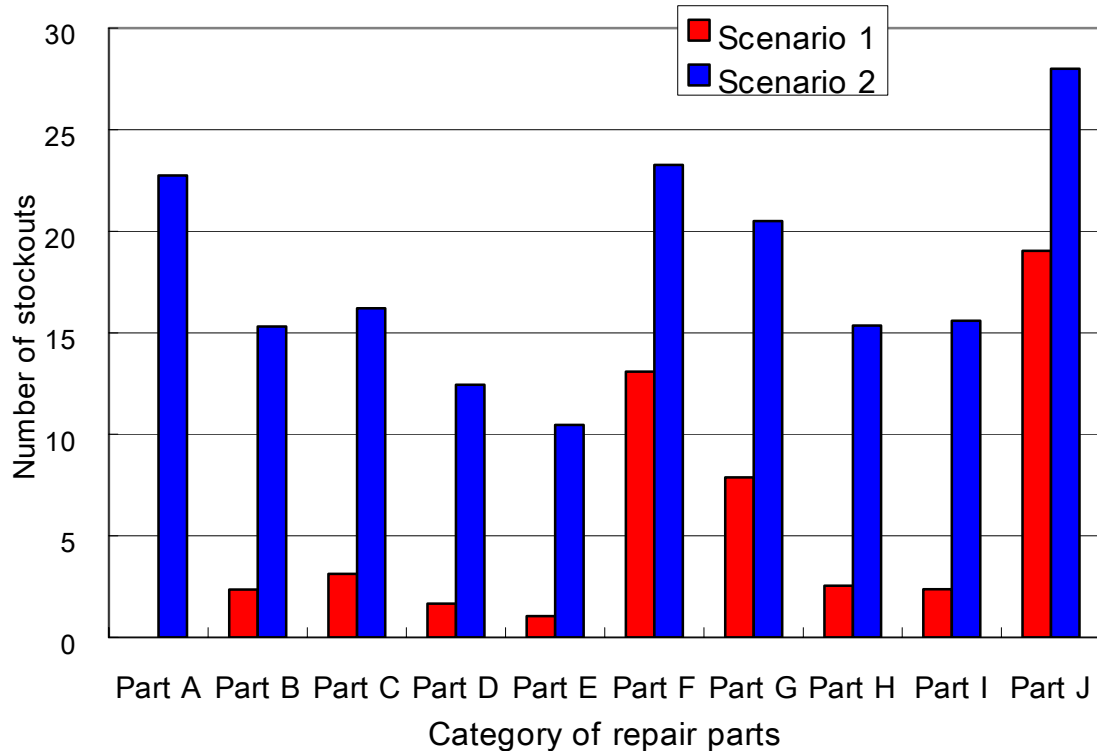


Figure 35. Chart of number of cases when stockouts of repair parts are occurred

Figure 35 displays the number of stockouts during the simulation time of ten years. It shows that all parts of "Scenario 2" have bigger values than "Scenario 1". This means that "Scenario 1" forecasts more precisely than "Scenario 2".

Approximately 1,700 of the K-1 TVs have received DLM over ten years, and the numbers of the y-axis scale and the differences between the two scenarios in Figure 35 look quite small in comparison with 1,700 cases. But these small differences lay out the significant difference of the total cycle time between the two scenarios. In other words, it is concluded that the reorder process of repair parts also significantly affects the result. This shows the importance of choosing an accurate forecasting methodology. In this

model, the coefficient of the weighted moving method is defined by only one way. As the coefficient value could be defined by several ways, the results could be different. Because of that, care must be taken when we conclude which method is better. It also becomes good research to run similar experiments and analyze the results after changing the coefficient of the weighted moving method.

b. Comparison of Changing Depot Schedules

This section will compare the efficiency of elements of Logistics Delay (LD) and explain methods and results about the analysis of LD by the exploration of depot schedules. Three scenarios are considered. These consist of the allocation of the K-1 TV based on the semester quota, the quarterly quota, or the smallest queue among two depots, are assumed for the comparison and the analysis. Table 12 shows the three scenarios used to compare LD in the experiment.

Scenario A	Quota K-1 TV per semester
Scenario B	Quota K-1 TV per quarter
Scenario C	Quota K-1 TV by checking the queue (finding smallest queue)

Table 12. Scenarios to compare Logistics Delay in the experiment

From a commonsense point of view, it can be expected that "Scenario C" is the best option that ROKA LSC can choose. This section will explain more detailed information as to why it is better than the others, as well as how much better.

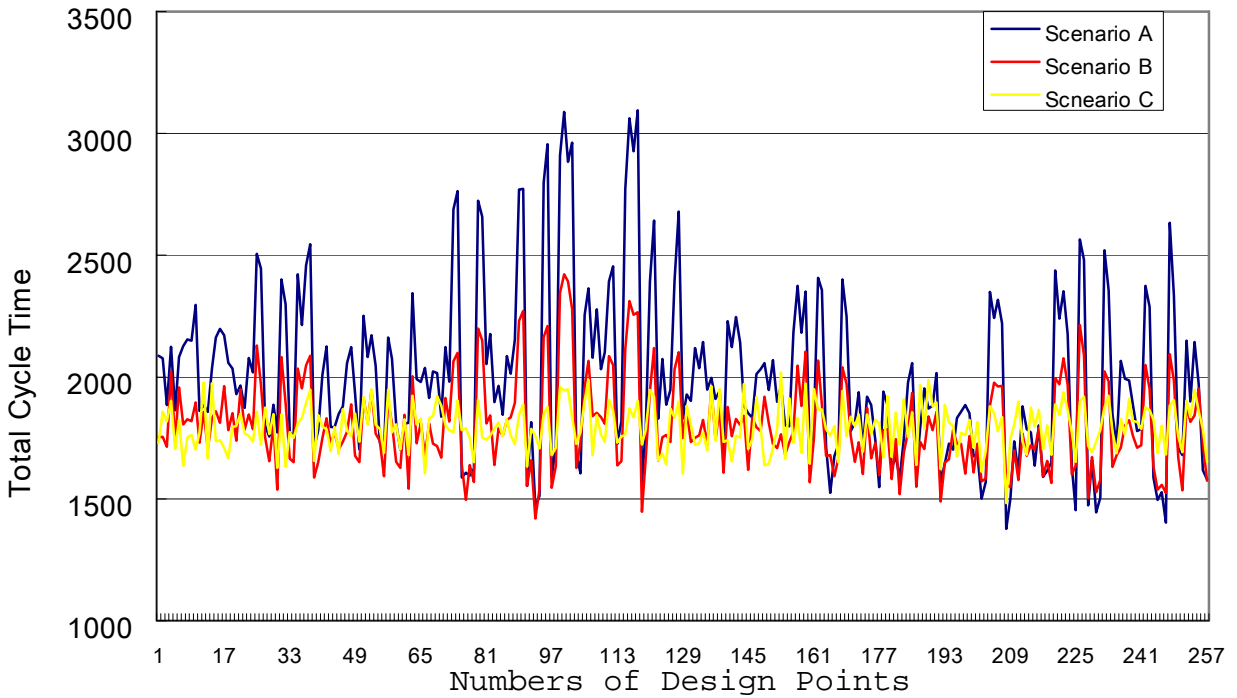


Figure 36. Plot of total cycle times of depot schedules

	Average(hrs)	Standard deviation(hrs)
Scenario A	2002.53	348.96
Scenario B	1802.31	188.66
Scenario C	1794.84	93.76

Table 13. Average and standard deviation values of scenarios

Figure 36 and Table 13 show that Scenario C has the smallest mean value and standard deviation among the three scenarios. It can be concluded this scenario can reduce the total cycle time and provide the most predictable output. It can be also evaluated which scenario has better results than the others or provides a predictable result by using a t-test as in the previous section.

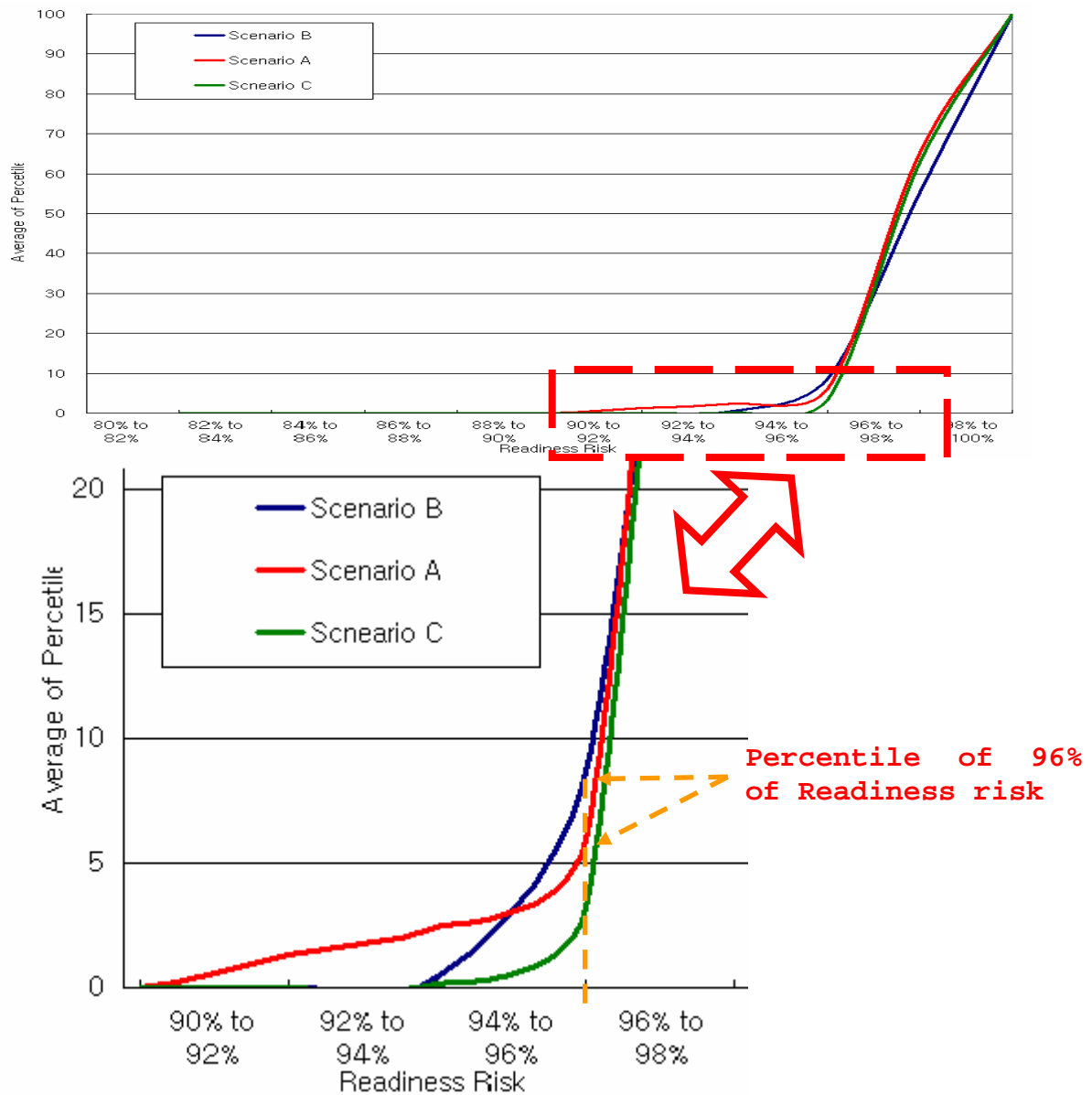


Figure 37. Cumulative curves of the readiness risk of each scenario and enlarged plot of Readiness Risk between 90% and 98% of readiness risk

Figure 37 displays the percentile of readiness risk of each scenario and the enlarged percentile of the range between 90% and 98% of readiness risk. The interesting thing to note here is that in the percentile of

readiness risk below 94%, Scenario A yields a higher result than Scenario B. Table 14 shows a comparison of these two scenarios.

	Average(hrs)	Stdev(hrs)	Cumulative Percentile of Readiness Risk from 90% to 96%
Scenario A	2002.52	348.95	5.99%
Scenario B	1802.31	188.66	8.68%

Table 14. Comparison of Scenario A and Scenario B

Even if Scenario B provides a smaller mean or standard deviation of total cycle time than Scenario A, it shows higher probability to provide the readiness risk below 94% than Scenario A. This means that it is not always a good choice to make a selection solely based on the comparison of the means or the standard deviations of the total cycle time.

D. ROBUSTNESS ANALYSIS

In this section, the robust design process and the analysis of results from the robust design are explained.

1. Factors Classification and Performance Evaluation

Factors are selected for the robust design from the five significant terms of the final regression model. Table 15 shows the step history of the five significant terms and consists of four interaction terms and one quadratic term.

Step	Parameter	R-Square
1	(TrainSchedule-368.193)*(Back_TrainSchedule-375.232)	0.5406
2	(TrainSize-7.18801)*(TrainSize_spread-5.99221)	0.604
3	(TrainSchedule_spread-119.362)*(TrainSchedule_spread-119.362)	0.6221
4	(Num_repairParts_needed_spread-1.94026)*(TrainSize_spread-5.99221)	0.6392
5	(Time_Final_Inspection-31.1022)*(Back_TrainSchedule_spread-117.453)	0.6488

Table 15. Five significant terms of the final regression model

In the robust design, factors are classified as decision factors that are controllable in the real world setting modeled by simulation, and noise factors that are not easily controllable or controllable only at a great expense in the real world setting.³⁰ Table 16 defines decision and noise factors for the robust design.

Decision factors	Noise factors
"TrainSchedule"	"TrainSize_spread"
"Back_TrainSchedule"	"TrainSchedule_spread"
"TrainSize"	"Num_repairParts_needed_spread"
"Time_Final_Inspection"	

Table 16. Decision factors and noise factors for the robust design

The robustness analysis is performed by specifying some performance characteristics of MOE, total cycle time in the depot, and an associated target value τ . The pattern of the performance characteristics around the target value can differ with the configuration of the decision

³⁰ Susan M. Sanchez, Robust Design: Seeking the best of all possible worlds, Proceeding of the 2000 Winter Simulation Conference, Operation Research Department, Naval Postgraduate School, Monterey, CA, 2000.

factors. In this model, if the performance characteristic's mean is equal to τ and its variance is equal to zero, then this is an ideal set of results for a configuration.

2. Response Surface Metamodel

The response value, or the total cycle time in the depot, is a function of the decision factors and the noise factors. It computes the sample average \bar{Y}_i and sample variance \bar{V}_i of n replications of i design point after running the model which has $i = 257$ design points with $n = 10$ replications.

$$\bar{Y}_i = \frac{1}{n} \sum_{j=1}^n \bar{Y}_{ij},$$

$$\bar{V}_i = \frac{1}{n-1} \sum_{j=1}^n (\bar{Y}_{ij} - \bar{Y}_{i\cdot})^2$$

These values are considered as new response values in the robust analysis, and the terms in the initial metamodels are obtained from the final regression model. The experiment design used allows for fitting at least a quadratic effect.

3. Analysis of the Results

The metamodels for the performance mean and the performance standard deviation are displayed below in Figure 38.

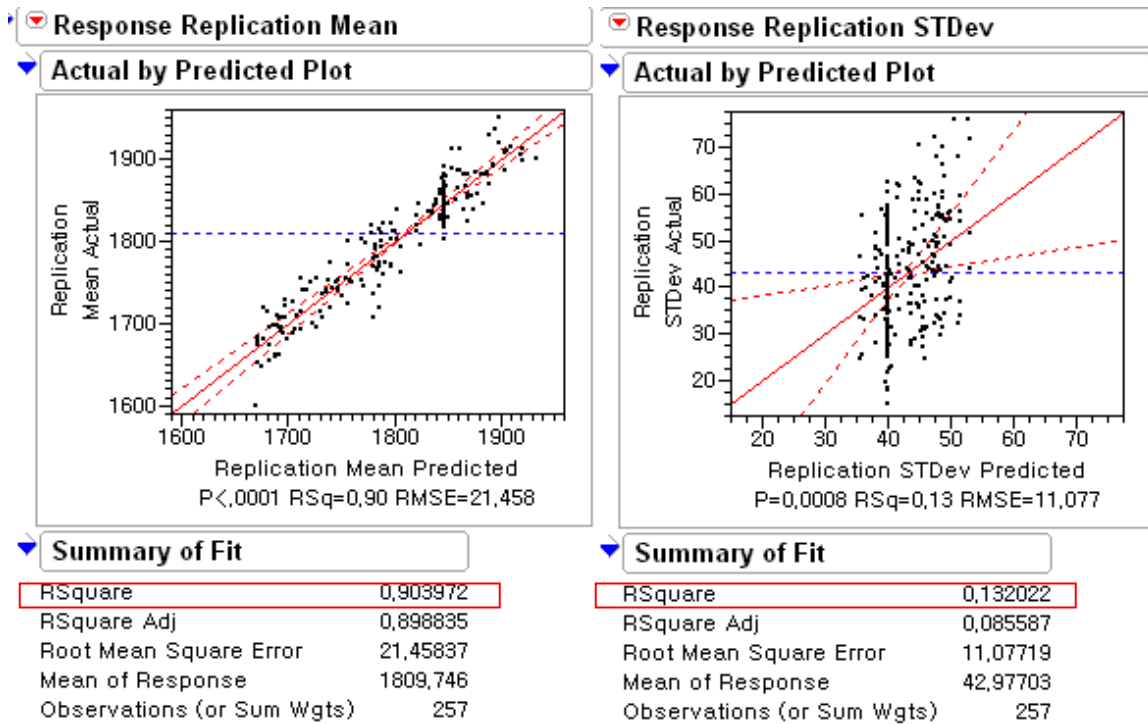


Figure 38. Actual by predicted plot for the performance mean and the performance standard deviation with five significant terms

The R-square value for the performance mean is 0.9039, and R-square value for the performance standard deviation is 0.13202. This shows the degree of the affect of the five significant terms on the mean and the variance of the performance. Figure 39 shows the prediction profilers of the terms.

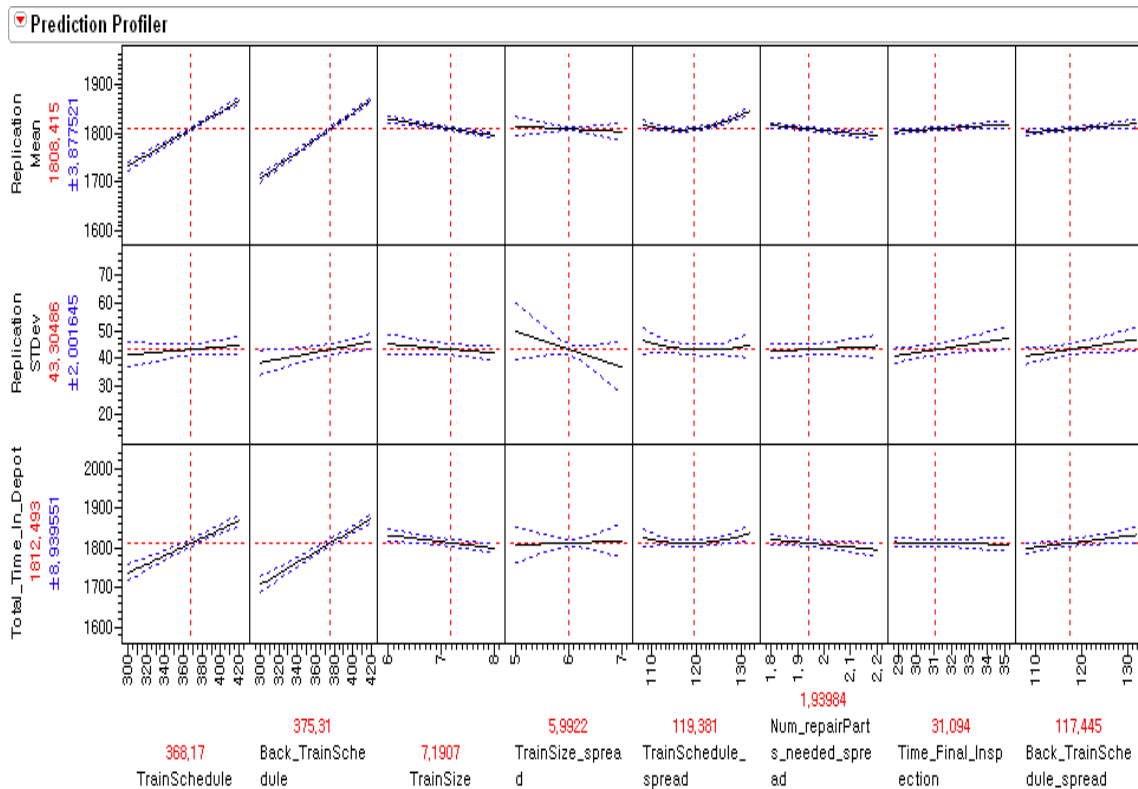


Figure 39. Prediction Profiler of factors of five significant terms

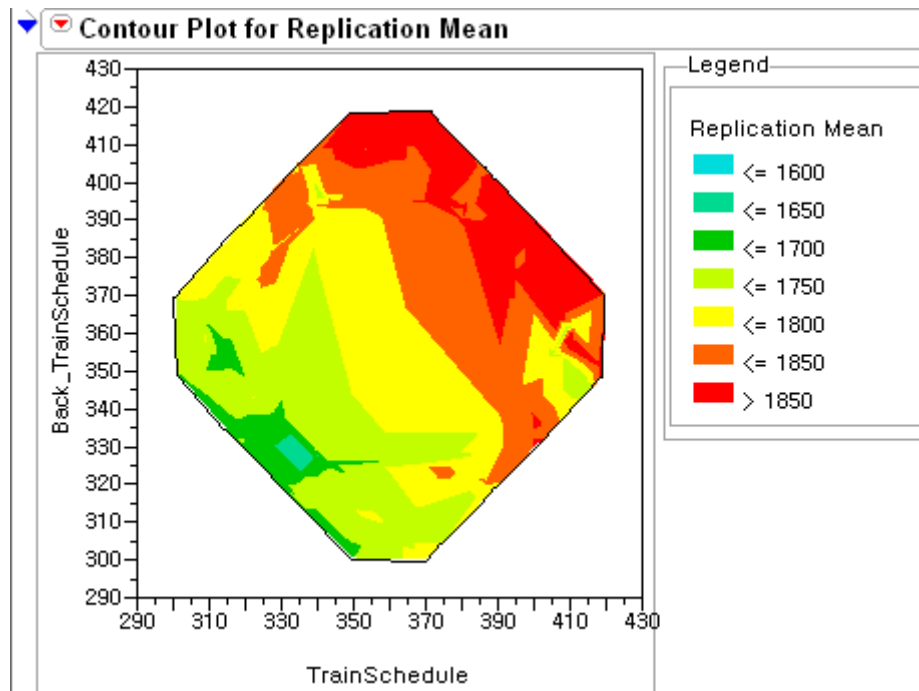


Figure 40. Contour Plot for the performance mean with "Back_TrainSchedule" and "TrainSchedule"

Decision factors, "TrainSchedule", "Back_TrainSchdule", and "TrainSize", strongly affect the performance mean and also affect the original output, "Total_Time_In_Depot". Figure 40 shows the relationship of two main factors. Both of them have a strong positive relationship to the performance mean.

The middle row in Figure 39 shows that the decision factors cannot have a large affect the variance of the performance. This means that these decision factors cannot decrease the variety of DLM system even though they can decrease the average of the total cycle time. Since the variety of the DLM system cannot be changed by the control of these decision factors, one needs to seek to identify factors that can further reduce the variability of the response.

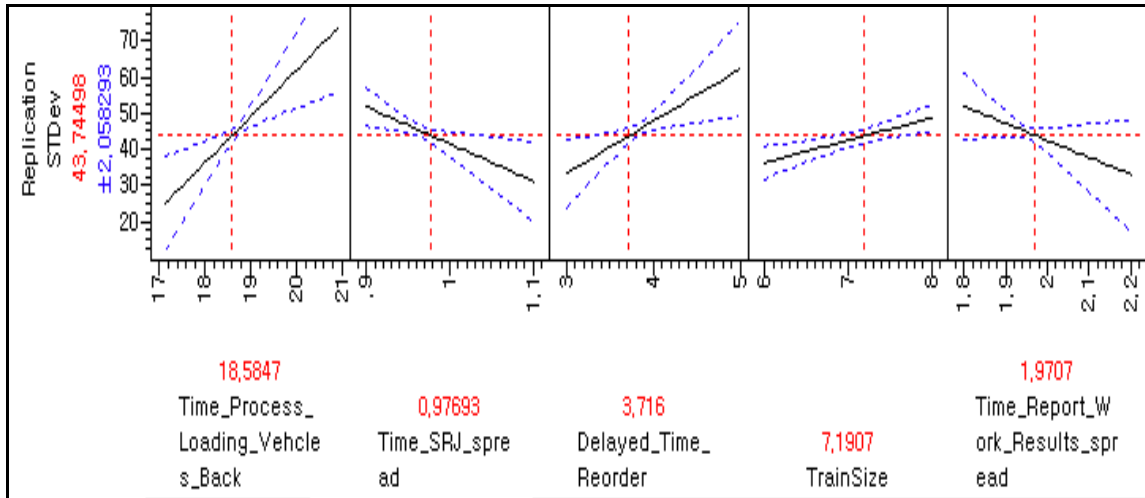


Figure 41. Prediction Profiler of main factors for the performance variance

Figure 41 is derived from the standard least square model with a R-square value of 0.6452. With the exception of "TrainSize", these factors are all different from those of Figure 39, and the performance variability is affected

with the other factors of the performance mean. If the model needs to decrease the variability of the performance characteristic, it should consider the factors of Figure 41, not the factors of Figure 39. Figure 41 also shows that the confidence interval widens as the factors go to the extreme values. This means that less precise predictions are possible when the factors have extreme values. Increasing the number of replications would narrow these confidence intervals. However, it is important to remember that these are confidence intervals for the mean response: a prediction interval for an individual response will be wider.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The purpose of this thesis was to show how to analyze the logistics elements of depot level maintenance in order to maximize the logistics support for the K-1 TV. All data used to embody the model were fictitious and assumed by the author based on his experience. For this reason, the results presented in this thesis do not represent the real world system; however, this thesis provides methodologies for how to approach to find optimal solutions.

In this thesis, the issues related to the logistics elements of DLM of the K-1 TV, configuration and modeling of DLM of the K-1 TV, and analysis of interactions of logistics elements were discussed. For efficient logistics support for DLM of the K-1 TV, ILS elements related to DLM of the K-1 TV were explained in Chapter II.

Chapter III explained the concepts about the model that embodies the process of DLM of the K-1 TV, the selection of a simulation tool and an analysis tool, and definition of variables that represent the logistics elements of DLM of the K-1 TV. Combat readiness and readiness risk were chosen as MOEs of the model that are very important issues among logisticians interested in keeping the strength of the K-1 TV. Since it ought to model the scenarios explained in Chapter II and has a large number of quantitative variables, NOLH was applied as a DOE of this model. Robust design was also applied to the model to analyze the performance characteristics.

Chapter IV showed the practical methods and processes of the analysis of logistics elements. It provided details

of the significant factors that affect the results and the interactions of the elements by the application of several regression methodologies. The conclusion from the data analysis suggests the following:

- Train schedules have the greatest effect on the total cycle time of DLM of the K-1 TV.
- Every factor included in the final regression model affected the result via interactions with one or more other factors. The most significant interaction is also the interaction of train schedules.
- The average combat readiness of the K-1 TV related to DLM over ten years is 98 percentile. However, it is not equivalent to MOE since the difference of combat readiness is too small by changing the 257 scenarios. In other words, DLM of the K-1 TV could not affect combat readiness of the K-1 TV so much.
- A simple moving average method is better than a weighted moving method since it decreases the total cycle time and the number of stockouts for repair parts.
- Quota of the K-1 TV by checking the smallest queue is better than quota K-1 TV per semester and quota K-1 TV per quarter. It gives the smallest mean and variance of the total cycle time.
- The five significant terms from the final regression model are displayed at Table 17. They strongly affect the performance mean. In other words, they are robust factors to affect the average total cycle time. However, the standard deviation of the total cycle time is hardly affected from these values. It means

that the precision of this simulation model is not affected by these factors.

Step	Parameter
1	$(\text{TrainSchedule}-368.193) * (\text{Back_TrainSchedule}-375.232)$
2	$(\text{TrainSize}-7.18801) * (\text{TrainSize_spread}-5.99221)$
3	$(\text{TrainSchedule_spread}-119.362) * (\text{TrainSchedule_spread}-119.362)$
4	$(\text{Num_repairParts_needed_spread}-1.94026) * (\text{TrainSize_spread}-5.99221)$
5	$(\text{Time_Final_Inspection}-31.1022) * (\text{Back_TrainSchedule_spread}-117.453)$

Table 17. Significant terms from the final regression model

These conclusions are based on simulation results. The input parameters in the simulation model were fictitious data due to the sensitivity of the data of ROKA. To minimize the sensitivity of the data, logisticians must look at all the ways in which the input parameters can represent the real world system as possible as it can. This is a difficult task due to the huge and the dynamic nature of logistics support for K-1 TV. Therefore, the guidance and the recommendation are introduced to provide a way to make a model to represent the real world system.

B. RECOMMENDATION OF FUTURE WORKS

This thesis has shown the procedures and the methodologies related to how the total cycle time of depot level maintenance is affected by various logistics elements. Though this thesis has shown how to analyze logistics elements, more reliable answers can be obtained by including other factors in the experimental design and assessing the results to see how they affect the MOEs. For this purpose, the author suggests the following five recommended future research areas.

Fist of all, various failure cases of the K-1 TV need to be assumed and the DLM of various failure cases should be different from each other. For example, assume that an engine of a K-1 TV is broken and ROK LSC decides to repair the engine only at the depot. This means that the transportation method will be changed from a train to trailers or trucks, and the repair process and the inventory service level will also be changed from the entire DLM of the K-1 TV. In further explanation, the demand of repair parts (RPs) and spare parts (SPs) depends on the failure cases and ought to be different from each other.

Second, a more detailed process of reordering parts is needed. In the model, ten RPs are considered and have the same inventory size and delayed time to reorder each of them. If it is assumed that they have different values independently, the model will be more reliable.

Third, the repair process of HRC and CMD needs to be reconsidered. In reality, they have different processes from each other. This model assumes that they have the same repair process (except the reorder process) since it is assumed that HRC is an outsource facility of CMD in the model. However, HRC is designed to manufacture the K-1 TV. It belongs to a civilian company, and CMD has different organizational structure from HRC. Even if they have the same capability of providing DLM of the K-1 TV, they each some repair process variables or variable ranges may differ across the organizations.

Fourth, if there are enough data related to the cost of processes during DLM of the K-1 TV, this approach can also analyze the total cost of DLM of the K-1 TV. Since the

budget for DLM of the K-1 TV is fixed and becomes a constraint in finding the optimal options of minimizing the total cycle time, all decisions of DLM of the K-1 TV should be concerned with the cost values of all processes of DLM of the K-1 TV. For example, this thesis just showed that the forecasting method can affect the total cycle time about the inventory service level (ISL). However, the ISL has several variables related to the cost values. For example, the cost of reordered repair parts (RPs) and spare parts (SPs), the cost of unscheduled orders of RPs and SPs, and the overhead cost of RPs and SPs. Since the reorder process costs a great deal of money and takes a large proportion of the entire budget for DLM of the K-1 TV, these variables might be significant factors, and the forecasting methods can more significantly affect the MOEs than the model without the assumption of the cost values. It will also be beneficial to conduct a more complete analysis to find out how the forecasting methods can affect the total cost of DLM of the K-1 TV. Labor costs and transport costs are among the other logistics elements. The analysis of the logistics elements with cost values will give much more precise and reliable results and make it possible to analyze the life cycle cost of the K-1 TV.

Finally, the analysis of other levels of maintenance for the K-1 TV will be good research to maximize the efficiency of the integrated logistics support (ILS) for the K-1 TV. Since the unit level of maintenance and the intermediate level of maintenance are also important as logistics supports for the K-1 TV, the analysis of these maintenance processes can increase combat readiness and decrease life cycle cost of the K-1 TV. For example, if ROK

LSC decides to supply a repair part stocked in the depot only to each post, a K-1 TV that needs the RP does not have to go to the depot, which means the combat readiness of this K-1 TV can be substantially improved. However, this requires a large budget to supply a RP to all the posts and a more precise forecasting method to decide the proper amount of a RP. It is very important to analyze these relationships and to find out the optimal relationship of all levels of maintenance of the K-1 TV.

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